The spatio-temporal distribution of zooplankton communities in the Southern Ocean south of Australia: high resolution sampling by the Continuous Plankton Recorder and its implications for long-term monitoring

by

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This thesis is dedicated to my parents,
Yola and George,
who instilled and nurtured my love of Life

Declaration

This thesis contains no material which has been accepted for the award of a degree or diploma by any other university or tertiary institution. To the best of my knowledge and belief this thesis contains no material previously published or written by another person, except where due acknowledgement is made in the text.

Brian P. V. Hunt

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Abstract

The Polar regions are considered to be particularly susceptible to the effects of climate change. Although there is evidence for warming in the Antarctic during the last century, few long-term ecological monitoring programmes have been initiated in this region. Zooplankton have been demonstrated to be excellent environmental indicators and in 1991 a Continuous Plankton Recorder (CPR) survey was established in the Southern Ocean south of Australia for monitoring purposes. Using data collected between October 2001 and March 2002 this thesis aimed to provide baseline data for the Southern Ocean CPR survey, and the first high resolution (~ 5 nm), ocean-basin scale sampling of zooplankton communities south of Australia.

As a primary step the sampling characteristics of the CPR were investigated by direct comparison of depth integrated NORPAC net samples with CPR samples (average depth ~ 10.5 m). Data were collected on a repeat transect along 140°E, between November and December 2001. Species richness and Shannon-Weaver diversity increased, while dominance decreased with depth. The CPR under-represented components of the zooplankton community relative to NORPAC samples from the equivalent depth zone (0-20 m), particularly fast moving and soft bodied taxa, however, both of these surface sample groups were characterised by high densities of *Oithona similis* and appendicularia. Multivariate analysis demonstrated that the CPR effectively identified the location of the biogeographic boundary represented by the Southern Sub-Antarctic Front (SAF-S).

After calibration of the CPR, two major components of natural ecosystem variability were investigated: spatial and temporal. The fine-scale horizontal structure of zooplankton communities was quantified from an 1170 nm transect along 140°E, conducted between 25 February and 3 March 2002. Six distinct zooplankton communities were identified, characterised by sharp boundaries which were strongly correlated with oceanographic fronts, demonstrating both the biogeographic importance of fronts and the sensitivity of zooplankton to their physical environment. The high degree of community complexity south of Australia reflected the regions unique oceanographic structure, characterised by multiple branches of the Sub-Antarctic Front, Polar Front, and Southern Antarctic Circumpolar Current Front. Zooplankton communities were also influenced by

phytoplankton community structure and mesoscale processes (e.g. eddy shedding, cross-frontal advection).

The seasonal component of temporal variability was investigated for two distinct regions, the SIZ and the Sub-Antarctic / Polar Frontal Zone (SAZ / PFZ). Six transects were completed in the SIZ between November and March along 140°E, where the SIZ is characteristically narrow. Zooplankton densities were low before ice melt (22-28 November transect). Peak densities (1963 ind.m^{-3}) were recorded on the 10-15 January transect, dominated by small copepods, large calanoid copepodites (C1-3), *Rhincalanus gigas*, foraminiferans, pteropods and appendicularians. The densities of these "Peak Community" taxa decreased through February and March. Conversely, the densities of > C4 copepodite *Calanoides acutus*, *Calanus propinquus* and *C. simillimus*, *Salpa thompsoni* (salps) and *Euphausia superba* (krill) increased through the season, and these taxa had become important community components by March.

Six transects were completed in the SAZ / PFZ at monthly intervals between October and March. Community structure was dominated by a small group of taxa throughout the season, including foraminiferans, *Oithona* spp., appendicularians, *Calanus simillimus*, *Rhincalanus gigas, Ctenocalanus citer, Clausocalanus* spp., pteropods and chaetognaths. Salps were an important component north of the SF-N throughout the season. Unlike the SIZ no seasonal shift in community structure was evident in the SAZ / PFZ. Peak densities to the north and south of the northern Sub-Antarctic Front were recorded in February and March respectively indicating a poleward lag in seasonal development.

The CPR was demonstrated to be an extremely effective sampling apparatus in the Southern Ocean. The high resolution spatial and seasonal data collected during this study gave unique insights into Southern Ocean zooplankton ecology, and provided a base against which future variability, both inter-annual and long-term, can be measured.

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Table of Contents

Chapter 1

Introduction

Fugue: A polyphonic composition, developed from a given theme or themes, according to strict contrapuntal rules. The theme is first given out by one voice or part, and then, while that pursues its way, it is repeated by another at the interval of a fifth or fourth, and so on, until all the parts have answered one by one, continuing their several melodies and interweaving them in one complex progressive whole..., in which the theme is often lost and reappears.

- http://dictionary.reference.com/search?q=fugue

1.1. The need for zooplankton monitoring in the Southern Ocean

The Southern Ocean comprises nearly 20% of the world oceans and is unique in that it circumnavigates the globe (El-Sayed 1998). It supports a large, multi-faceted ecosystem, including a dynamic open ocean region with numerous sub-systems, and the interlinked seasonal sea-ice and continental shelf zones (Knox 1984, Hempel 1985, Smith and Sakschaug 1990, Smith and Schnack-Schiel 1990). The Southern Ocean plays an important role in global biogeochemical cycles e.g. it is a major sink of silicate (Honjo et al. 2000, DeMaster 2002), is considered to play an important role in the drawdown of carbon dioxide (Metzl et al. 1999, McNeil et al. 2001, Trull et al. 2001a), and is responsible for > 25% of global dimethylsulphide emission (Curran and Jones 2000). The global influence of the Southern Ocean extends further to the formation of oceanic bottom water and atmospheric heat flux (Foster 1984, Knox 1984).

In recent years much interest has been shown in the biological impacts of climate change, including warming and ozone depletion, in Antarctic and Southern Ocean ecosystems (e.g. Arrigo 1994, Marchant 1994, Croxall et al. 2002, Weimerskirch et al. 2003). Polar ecosystems are likely to be the first affected by global climate change (Zwally 1994). Evidence indicates that a warming of air and sea temperature (Smith and Steenkamp 1990, Aoki et al. 2003, Weimerskirch et al. 2003), and a reduction in sea-ice extent (de la Mare 1997) has already occurred during the last century, while ozone depletion and enhanced UV radiation are well documented over Antarctica (Zwally 1994). However, although the need for

monitoring in the Antarctic has been formally recognised by the Madrid Protocol (SCAR 1993), few systematic long-term and large-scale ecological studies have been initiated to research the ecosystem impacts of environmental change in this region (El-Sayed 1998).

Many zooplankton species have wide distributions but exhibit preferences for specific environmental conditions within their range. Other species are stenotypic (e.g. Raymont 1983, Everson 1984, Rutherford et al. 1999) and physical changes (e.g. temperature) are therefore expected to have a significant impact on species distributions and community structure. There is also a growing body of evidence that plankton may be strongly affected by ozone depletion and increased UV radiation (Hader et al. 1993, Malloy et al. 1997, Kouwenberg 1999, Newman et al. 1999). The combination of environmental sensitivity, short life histories, and inability to escape their surroundings, makes zooplankton excellent indicators of environmental change.

"*...plankton can integrate meteorological variability and as such may have value in mapping the environmental consequences of climate change in the marine environment.*"

- Reid et al. 1998a, page 282, paragraph 2

Zooplankton play a major role in all of the Southern Ocean sub-systems, functioning as grazers, predators and scavengers (Verity and Smetacek 1996, Mayzaud et al. 2002), and ultimately providing the link between primary producers and the upper trophic levels represented by predators including squid, fish, seabirds, seals and whales (Knox 1984, Hempel 1985, Ainley and DeMaster 1990, Murphy 1995, Fraser and Hofmann 2003). In addition, zooplankton are vital components of biogeochemical cycles, contributing to vertical flux of both organic and inorganic matter (e.g. faecal pellets and empty pteropod tests), or retarding vertical flux through scavenging of suspended particles (Gonzalez and Smetacek 1994, Honjo et al. 2000, Marine Zooplankton Colloquium 2002, Dagg et al. 2003, Priddle et al. 2003). Contributions to biogeochemical flux vary substantially between species (Smetacek et al. 1990, Huntley et al. 1991, Longhurst 1991, Priddle et al. 2003), and as a result flux will be impacted on by zooplankton community structure and the resulting inter-species interactions. Therefore, environmentally forced changes in

zooplankton community structure may have important implications for ecosystem functioning.

Localised, generally sea-ice zone and krill orientated (*Euphausia superba*) plankton monitoring programs have been initiated in the Antarctic, including the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Ecosystem Monitoring Program (C-EMP) (Agnew 1997) and the Long-Term Ecological Research (LTER) program. C-EMP was initiated in 1985 and focuses on krill / predator interactions in the Antarctic Peninsula region, South Georgia and Prydz Bay, while LTER was initiated in 1990 at Palmer Station, west of the Antarctic Peninsula, and focuses on sea-ice zone ecology (El-Sayed 1998). However, prior to the inception of the Southern Ocean Continuous Plankton Recorder (SO-CPR) Survey only one large-scale (ocean basin) plankton survey had been established in the Southern Ocean. This survey is operated by the Japanese Antarctic Research Expedition (JARE), and has conducted routine sampling in the Southern Ocean between South Africa and Tasmania since 1972, using NORPAC nets with a very coarse sampling resolution (~ 300nm) (Takahashi et al. 1998).

1.2. The Continuous Plankton Recorder: history and application

Long term records of plankton in other oceans have identified significant correlations between plankton distribution, biomass and production, and large scale oceanographic variability and climatic trends (e.g. Colebrook 1986, Aebischer et al. 1990, Cushing 1990, Roemmich and McGowan 1995, Taylor 1996, Verheye and Richardson 1998, Verheye et al. 1998, Hare and Mantua 2000). Perhaps the most notable plankton monitoring program is the Continuous Plankton Recorder (CPR) survey, operating in the North Sea and north Atlantic. This monitoring program was initiated in the 1930's and continues to this day under the auspices of the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), providing the only long-term plankton dataset of its kind on the scale of the ocean basin (Reid et al. 2003).

The CPR was conceived by Sir Alister Hardy in order to overcome one of the fundamental problems faced by plankton biologists (Hardy 1936a).

"*The composition of the plankton is in qualitative as well as quantitative relations very irregular, and the distribution of the same in place and time in the ocean also very unequal*"

– Ernst Haeckel (1890): in Hardy 1936b, page 513 paragraph 3

In addition to the patchy nature of plankton communities, their distributions may change rapidly with the flow of ocean currents (Hardy 1936a). Traditional zooplankton collection procedures, including vertical and obliquely towed nets, are time consuming and are characterised by the spatial incongruity of sample points. These methods are therefore not suitable for the purpose of obtaining a clear picture of plankton distribution patterns over a large area at any one time.

"*...it seemed desirable to construct a machine which could be towed at full speed at any required depth below the surface and sample the plankton mile after mile so as to give a continuous record of the main changes in its composition along the line of the tow*"

– Hardy 1936a, page 460, paragraph 2

The CPR was designed to fulfil these criteria. In addition, the CPR needed to be relatively easy to use as Hardy envisioned enlisting merchant ships to provide regular CPR transects across the North Sea. The prototype CPR was in fact first used in the Southern Ocean, during the 1925-27 expedition of the R. R. S. Discovery (Hardy 1926). Design problems encountered on this voyage were rectified on return to the UK. The improved Mark II model was deployed in September 1931, on a transect from Hull to Hamburg, but the CPR survey proper commenced in June 1932 (Reid et al. 2003).

Since 1931 only minor design changes have been made to the CPR, but the fundamental sampling characteristics have largely remained the same (Reid et al. 2003). Essentially the CPR is a robust easy to use plankton sampling instrument that can be towed at 5-20 knots behind any large vessel with a suitable towing winch. Plankton are collected continuously on a roll of silk and integrated into segments representing a pre-determined distance along the transect (10nm in the northern hemisphere survey). In combination, these characteristics enable zooplankton surveys with large spatial coverage as well as high temporal resolution to be conducted rapidly and frequently. The CPR has a towing depth of ~ 6.7m (Hays and Warner 1993), and therefore focuses attention on the surface layers of the ocean, while the combination of small mouth area (1.6cm^2) and relatively fine mesh (270μm) means that sampled zooplankton are predominantly in the

mesozooplankton size range (0.5mm to 10mm) (Robertson 1968, Colebrook 1986, Warner and Hays 1994).

Through the course of the survey the CPR data set has developed by an accumulation of data on numerous ecological levels. Single transects and annual data sets have been used to investigate the spatial distributions of zooplankton (Rees 1951, Tibbo et al. 1958, Colton and Marak 1962, Bainbridge and Cooper 1973, Lindley 1982a, Williams et al. 1993, Clark et al. 2001). Annual and inter-annual data have provided insights into population cycles and the seasonality of zooplankton communities (Lindley and Williams 1980, Lindley 1980, Lindley 1982b,c, Robinson et al. 1986, Lindley 1988, Brander 1994, Bryant et al. 1997). Due to its shallow sampling depth, the CPR data is strongly affected by the vertical distribution of plankton (Hardy 1936b, Hardy 1939). Although the CPR data can not be used to examine the amplitude of migration (Hays et al. 1997), they have provided insights into diel (Hays et al. 1994, Hays 1995a,b, Hays et al. 1997, Beaugrand et al. 2001) and seasonal (Williams and Robins 1981, Williams and Lindley 1982, Lindley 1987, Hays 1995b, Hays et al 1995, Beare and McKenzie 1999a) cycles of vertical distribution.

Analysis of time series data has identified regionally specific cycles in community structure and development (Madden et al. 1999, Beaugrand et al. 2001), and demonstrated inter-annual changes in plankton abundance (Gieskes and Kraay 1977, Colebrook 1985, Owens et al. 1989, Jossi and Goulet 1993, Lindley et al. 1995, Planque and Fromentin 1996, Sameoto 2001), migration behaviour (Hays et al. 1996, Beare et al. 1998, Hirst and Batten 1998, Beare and McKenzie 1999b), seasonality (Broekhuizen and McKenzie 1995, Planque and Fromentin 1996), and identified relationships between trophic levels (Colebrook 1979, Colebrook 1984, Roff et al. 1988, Greenstreet et al. 1997, Sameoto 2001). Integration of inter-annual data sets has facilitated the production of detailed distribution maps of species, communities and biodiversity, and subsequently the definition of ecotones (Beaugrand et al. 2000, Beaugrand and Ibanez 2002, Beaugrand et al. 2002a,b, Continuous Plankton Recorder Survey Team 2004).

Knowledge of communities based on historical CPR data has enabled hydrographic events / variability to be recognised e.g. through the presence of indicator / expatriate species (Reid et al. 1983, Lindley et al. 1990, Reid et al. 1992, Stephens et al. 1998, Corten 1999, Edwards et al. 1999, Johns et al. 2001, Beaugrand et al. 2002a). Long-term changes in plankton densities and community

structure have been linked to large scale ocean and climate cycles and warming trends in the northern hemisphere (Colebrook et al. 1978, Colebrook 1986, Taylor et al. 1992, Hays et al. 1993, Taylor 1995, Taylor 1996, Reid et al. 1998b, Beare and McKenzie 1999a, Hare and Mantua 2000, Conversi et al. 2001, Reid et al. 2001, Beaugrand et al. 2002b), while anthropogenic disturbance, e.g. eutrophication, has also been implicated (Brander et al. 2003). Furthermore, changes in the plankton have been shown to propagating upwards through the ecosystem, affecting higher trophic levels (Aebischer et al. 1990, Beaugrand et al. 2003, Corten and Lindley 2003), including commercially exploited fish populations (Reid et al. 2001, Beaugrand et al. 1993, Beaugrand and Reid 2003, Reid et al. 2003).

These above observations highlight the value of plankton as indicators of environmental change and forecasters of ecosystem change. In 1939 Hardy said of the CPR survey:

"*The idea underlying the initiation of this ecological survey was that of attempting to apply methods similar to those employed in meteorology to a study of the changing plankton distribution, its causes and effects.*"

- Hardy 1939, page 1 paragraph 1

Ultimately the northern hemisphere CPR survey achieved Hardy's aim.

1.3. The Southern Ocean CPR Survey

Given the need for monitoring, and the proven success of the CPR in the northern hemisphere, a sister survey was established in 1991 i.e. the SO-CPR Survey (Hosie et al. 2003). Initially the SO-CPR Survey's primary purpose was to monitor zooplankton distribution patterns and the annual production and development of krill (*Euphausia superba*) larvae in the sea ice zone. In 1996 the survey was expanded to include routine sampling in the permanently open ocean zone (POOZ) south of Australia, taking advantage of resupply routes between Tasmania and Australia's Antarctic stations, and dedicated marine science voyages. The SO-CPR Survey thus became only the second long-term, large-scale (ocean basin) plankton monitoring program in the Southern Ocean. Since 1997 an average of 6946nm of CPR tows have been completed per annum, aboard the Australian research and supply vessel the *Aurora Australis* (Table 1.1). In addition, since 1999

a further 3414nm per annum have been collected aboard Japanese research vessels. Together these tows have provided extensive spatial coverage in the Southern Ocean south of Australia, including samples from all months of the year with the exception of June (Figure 1.1, Table 1.2).

The success of the SAHFOS CPR survey has valuable lessons for the monitoring of environmental change by the Southern Ocean sister survey. Possibly most fundamental is that continuity is required in both the distribution of sampling effort, spatially and temporally, and sampling methodology in order to detect long-term changes. However, of major importance for the establishment of a monitoring program is characterisation of the baseline conditions (biological and physical) in the monitoring area. This provides a starting point against which future variability can be measured, hence enabling environmental and related ecosystem change to be recognised through changes in plankton community structure. Characterisation of baseline conditions involves two important steps. Firstly, the sampling characteristics of the monitoring tool need to be established. This has the dual function of defining what the collected samples represent (calibration) and enabling them to be analysed in the light of existing knowledge. Secondly, natural ecosystem variability needs to be assessed using the 'calibrated' monitoring tool. A basic tenet of monitoring is that species and communities are in part a reflection of the environment, and therefore assessment of natural variability needs to explicitly examine the role of the environment in shaping the ecology.

In addition to being a long-term monitoring tool, the northern hemisphere CPR survey has provided valuable insights into the ecology of zooplankton species and communities on multiple spatial and temporal scales (Section 1.2.). A review of the literature indicates that, in terms of zooplankton, the region south of Australia is one of the least studied areas of the Southern Ocean. A relatively large amount of research has been completed in the vicinity of Prydz Bay (Hosie and Cochran 1994, Hosie 1994), and in the sea-ice zone east of this region (Hosie et al. 2000, Nicol et al. 2000a,b, Chiba et al. 2001). However, the majority of Southern Ocean zooplankton research has been conducted in the Weddell Sea (e.g. Hubold et al. 1988, Kaufmann et al. 1995, Metz 1995, Vuorinen et al. 1997, Schnack-Schiel et al. 1998), Ross Sea (Foster 1989, Granata et al. 2002, Seibel and Dierssen 2003), Antarctic Peninsula (e.g. Hopkins 1985a,b, Siegel and Piatkowski 1990, Schnack-Schiel and Mujica 1994, Ross et al. 1998, Zmijewska et al. 2000), Scotia Sea

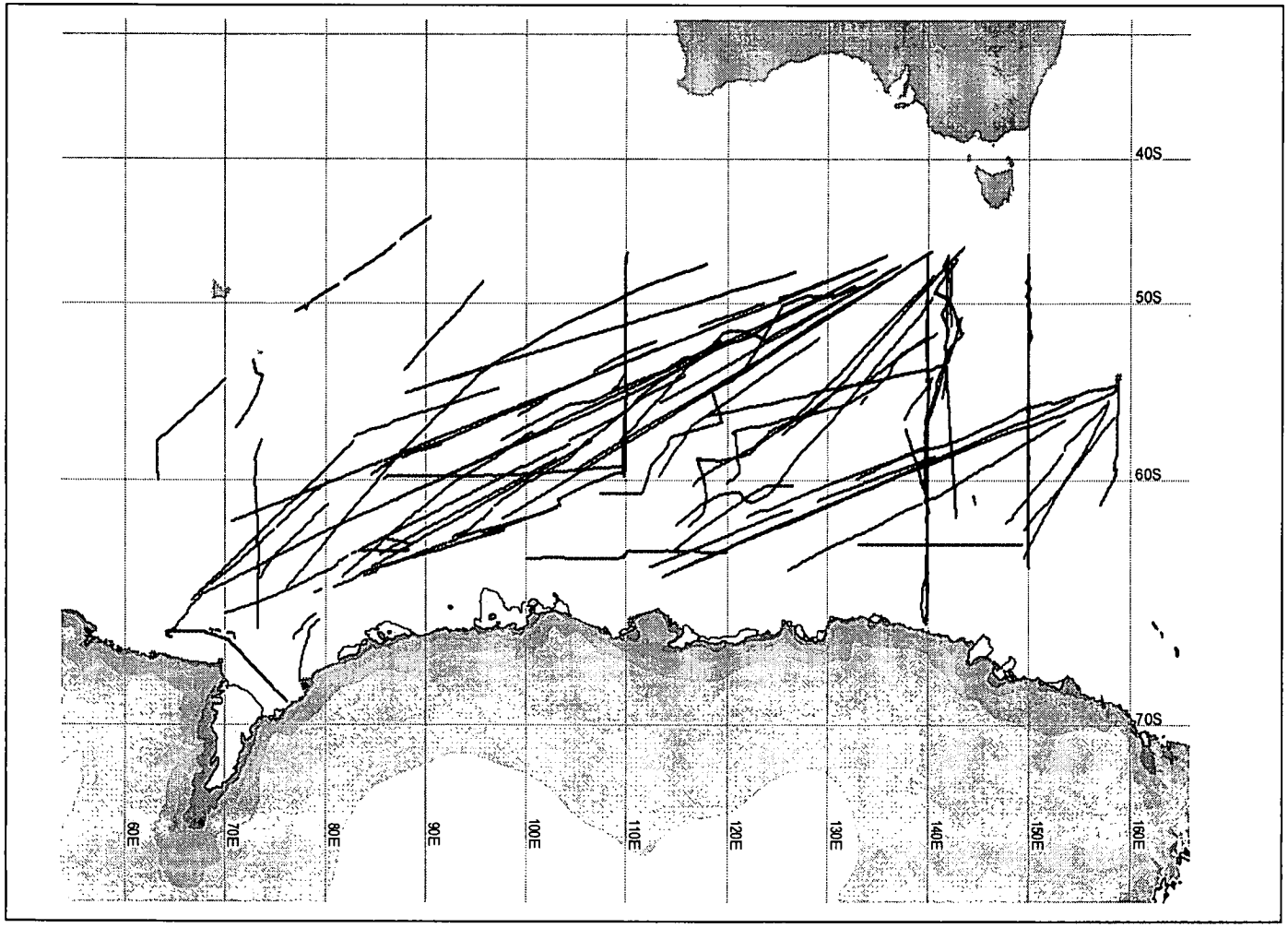
Table 1.1. Summary of the mileage (nm) completed, and the contributions of the Australian Antarctic Division's *Aurora Australis* and Japanese vessels, by the Southern Ocean Continuous Plankton Recorder Survey since its inception in 1990 / 91.

	Mileage		
Season	***Aurora Australis***	**Japanese Ships**	**Total**
1990 / 91	1086.98		1086.98
1991 / 92			
1992 / 93	480.65		480.65
1993 / 94	342.47		342.47
1994 / 95			
1995 / 96	459.19		459.19
1996 / 97	1524.55		1524.55
1997 / 98	7734.54		7734.54
1998 / 99	3267.90		3 267.90
1999 / 2000	7407.14	3095.89	10518.17
2000 / 01	8543.51	1928.86	10472.38
2001 / 02	7857.52	5351.79	13209.31
2002 / 03	9299.82	*Being processed...*	9299.82
2003 / 04	*Being processed...*		

Table 1.2. Summary of months sampled (shaded grey and marked with 'Y') for each year since the inception of the Southern Ocean Continuous Plankton Recorder Survey in 1990 / 91.

	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1990												
1991	Y		Y									
1992												
1993	Y	Y										
1994												
1995								Y				
1996												
1997				Y					Y		Y	Y
1998	Y	Y			Y		Y				Y	
1999			Y	Y			Y	Y		Y		Y
2000	Y	Y	Y							Y		Y
2001	Y		Y							Y		Y
2002	Y	Y	Y							Y	Y	Y
2003	Y		Y							*Being processed..*		
2004	*Being processed...*											

Figure 1.1. Map illustrating the spatial coverage of Continuous Plankton Recorder (CPR) sampling in the Southern Ocean south of Australia since the inception of the CPR Survey in 1990 / 91.



(e.g. Hopkins et al. 1993, Atkinson et al. 1997, Ward et al. 1997) and at the sub-Antarctic and Antarctic Islands (e.g. Atkinson et al. 1990, Perissinotto 1992, Razouls et al. 1996, Razouls et al. 1998).

NORPAC net samples have been collected on an interannual basis, by JARE, in the open ocean south of Australia since 1972. However, these samples are few (~ 18 / year) and widely spaced (~ 300nm resolution), and consequently have provided only a preliminary insight into the zooplankton community dynamics of the region (Takahashi et al. 1998). Therefore, in addition to providing long-term data for monitoring purposes, CPR sampling has provided the first high resolution large-scale zooplankton sampling in the Southern Ocean south of Australia. In the light of the pivotal role played by zooplankton in pelagic ecosystems, this may provide important insights into the functioning of the region.

1.4. Thesis Objectives

This thesis had the dual, and intrinsically linked aims of providing baseline data for the long-term Southern Ocean CPR Survey and providing the first detailed spatio-temporal analysis of zooplankton communities in the Southern Ocean south of Australia (Table 1.3). As a primary step Chapter 3 will investigate the sampling characteristics of the CPR. In the light of the shallow sampling depth of the CPR, a major requirement of this "calibration" was quantification of the fine-scale vertical distributions of zooplankton. Chapters 4 to 6 investigate two fundamental components of natural ecosystem variability, essential for the identification of ecological change in a monitoring programme: spatial and temporal variability. Chapter 4 quantified the fine-scale horizontal structure of zooplankton communities, focussing explicitly on their relationship to the physical oceanographic environment, while Chapters 5 and 6 quantified the seasonal component of temporal variability. Finally, Chapter 7 collated observations from these four data sets, and assessed the utility of the CPR as a long-term monitoring apparatus in the Southern Ocean.

Table 1.3. Illustration of the relationship between the dual aims of this thesis: **1.** providing baseline data for the long-term Southern Ocean CPR Survey and **2.** providing the first detailed analysis of zooplankton communities in the Southern Ocean south of Australia.

	Southern Ocean Zooplankton Ecology		**Continuous Plankton Recorder Survey**
Chapter 3	Fine-scale depth distribution of zooplankton	⟷	Calibration of the CPR
Chapter 4	Fine-scale spatial distribution of zooplankton communities in relation to the physical environment	⟷	Spatial variation of zooplankton communities
Chapter 5	Seasonal succession of zooplankton communities in the Seasonal Ice Zone	⟷	Seasonal variability of zooplankton communities
Chapter 6	Seasonal succession of zooplankton communities in the northern Southern Ocean – the Sub-Antarctic to the Polar Frontal Zones	⟷	

Chapter 2

Study Area and General Methods

2.1. Data Collection and Study Area

Data for this thesis were collected on five voyages, conducted between October 2001 and March 2002 from four vessels, operated in collaboration by the Australian Antarctic Division (AAD) and the National Institute of Polar Research, Tokyo. Sampling focussed on the 140°E meridian (Figure 2.1). As data collection differed for each component of this thesis, sampling details are presented individually for each chapter. A full list of samples collected is presented in Appendix 1.

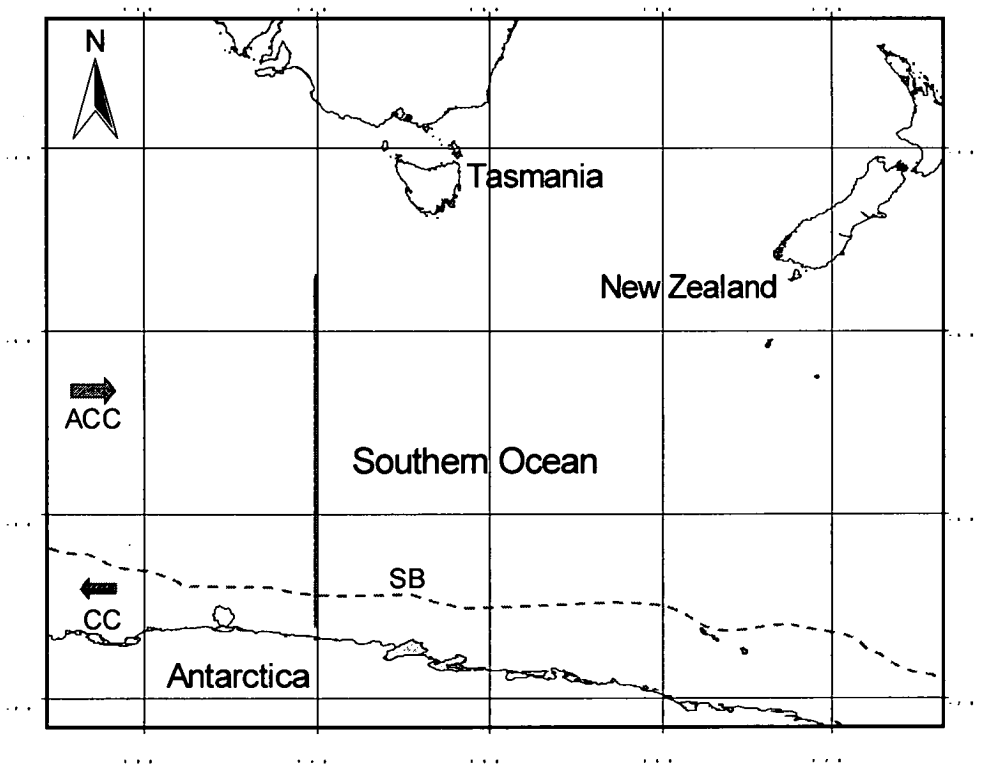


Figure 2. 1. Map illustrating the study area south of Tasmania, and highlighting the 140°E meridian, the primary focus of the study. ACC – Antarctic Circumpolar Current; CC – Coastal Current; SB – Southern Boundary of the ACC.

2.2. Oceanographic Structure of Study Area

The Southern Ocean is dominated by the Antarctic Circumpolar Current (ACC), the only zonal current that is unobstructed by continental land masses (Foster 1984). The ACC flows eastwards around the Antarctic continent, driven by the prevailing westerly winds (and hence otherwise known as the West Wind Drift) in the region between ~ 45°S and ~ 60°S (Foster 1984; Orsi *et al.* 1995). South of ~ 60°S easterly winds prevail producing the westward flowing Antarctic Coastal Current (East Wind Drift). However, the Coastal Current (CC) is not continuous around the Antarctic continent, being broken by a series of gyres, including those in the Weddell and Ross seas (Foster 1984).

A strong gradient exists in the distribution of physical properties across the Southern Ocean and there is a transition from warm, light Sub-Tropical water in the north to cold, dense Antarctic water in the south. Deacon (1937) was the first to note that this transition took place in a step-like fashion, rather than as a gradual change. The zones of enhanced meridional gradients, or fronts, have been shown to be consistent features, generally of circumpolar extent, and separate zones of relatively uniform water mass properties (e.g. Emery 1977, Lutjeharms and Vallentine 1984, Hofmann 1985, Nowlin and Klinck 1986, Belkin and Gordon 1996, Veth et al. 1997). The fronts are deep reaching features, extending to the sea-floor, with high current velocities (20-50cm.s^{-1}) relative to the inter-frontal zones (< 10cm.s^{-1}) (Sokolov and Rintoul 2002). In addition the fronts are responsible for most of the volume transport of the Southern Ocean, with, for examples, the SAF along 140°E having a mean transport of 105 svedrups out of 147sv across the entire ACC (Rintoul and Sokolov 2001, Rintoul and Trull 2001).

2.2.1. Circumpolar frontal structure

The seminal paper by Orsi et al. (1995) collated all historical oceanographic sections prior to 1990 to provide unified definitions of frontal structure and their locations. This work was an important contribution to Southern Ocean oceanography as the application of consistent frontal definitions across regions enabled circumpolar comparison of their positions. The frontal locations defined by Orsi et al. (1995) are depicted for the region south of Australia in Figure 2.2. These

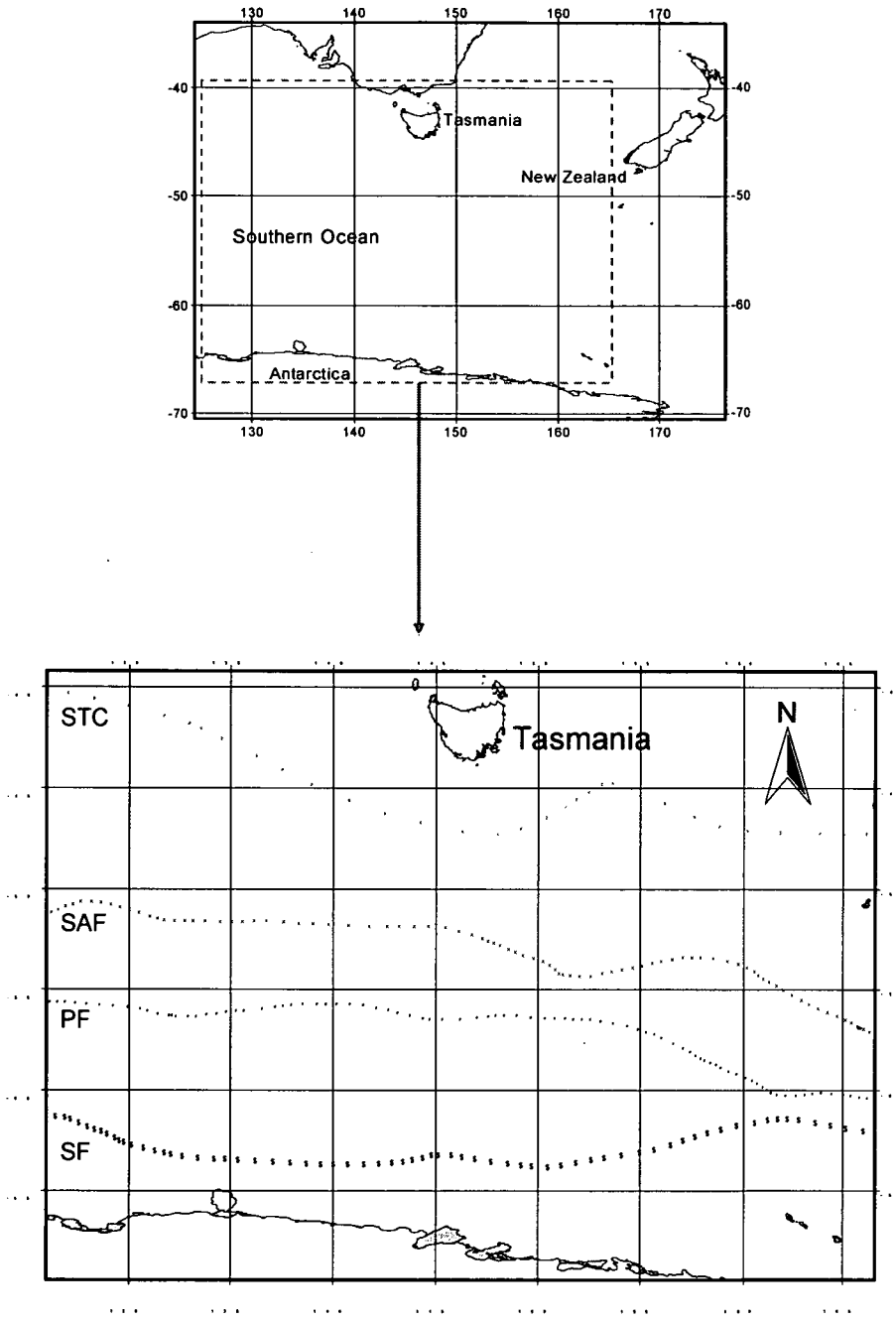


Figure 2.2. Location of fronts defined by Orsi et al. (1995) in the Southern Ocean South of Australia.

authors recognised the Sub-Tropical Convergence (STC) as the northern most front of the ACC, separating Sub-Antarctic Surface Water (SASW) from the warmer (> 11°C) and saltier (> 34.9) Sub-Tropical Surface Water (STSW). The STC is generally characterised by large property gradients, surface temperature changing by as much as 4-5°C and salinity by 0.5.

The SASW characterises the Sub-Antarctic Zone (SAZ), bounded in the north by the STC and in the south by the Sub-Antarctic Front (SAF). Orsi et al. (1995) defined the location of the SAF by the rapid northward sinking of the salinity minimum associated with Antarctic Intermediate Water (AAIW), from near the surface in the Polar Frontal Zone (PFZ) to depths greater than 400m in the SAZ. This gives a similar position to the SAF as Belkin and Gordon's (1996) definition of the SAF by axial T-S indices of 7°C / 34.3 at 200m. The SAF forms the northern boundary of the Polar Frontal Zone (PFZ) while the southern boundary of the PFZ is the Polar Front (PF). The PF is also the northern most extent of Antarctic Surface Waters (AASW). The PF is commonly defined by the northern extent of the 2°C isotherm demarcating the sub-surface temperature minimum (θ_{min}) in the 200m layer (Orsi et al. 1995, Belkin and Gordon 1996).

South of the PF Orsi et al. (1995) identified a new front which they have termed the Southern Antarctic Circumpolar Current Front (SACCF). For the purpose of this thesis I have abbreviated this to the Southern Front (SF). The SF is the only Southern Ocean front that does not separate distinct surface water masses, and is identified by θ_{max} 1.8°C at 500m and S_{max}34.73 at > 800m (Orsi et al. 1995). South of the SF is the Southern Boundary (SB), representing the southern limit of the eastward circulating ACC, and is best defined by the southern limit of the oxygen minimum associated with Upper Circumpolar Deep Water (UCDW).

2.2.2. Frontal structure south of Australia

Recently, Sokolov and Rintoul (2002) undertook a detailed, regionally specific analysis of the physical oceanography south of Australia. Using a combination of historical CTD / XBT data collected along 140°E and satellite altimetry data they identified a unique frontal structure in this region, differing somewhat from that of Orsi et al. (1995). In particular Sokolov and Rintoul identified two branches (a northern and southern) of each of the SAF, PF and SF (Figure 2.3), while the property gradients of the STC were found to be weak relative

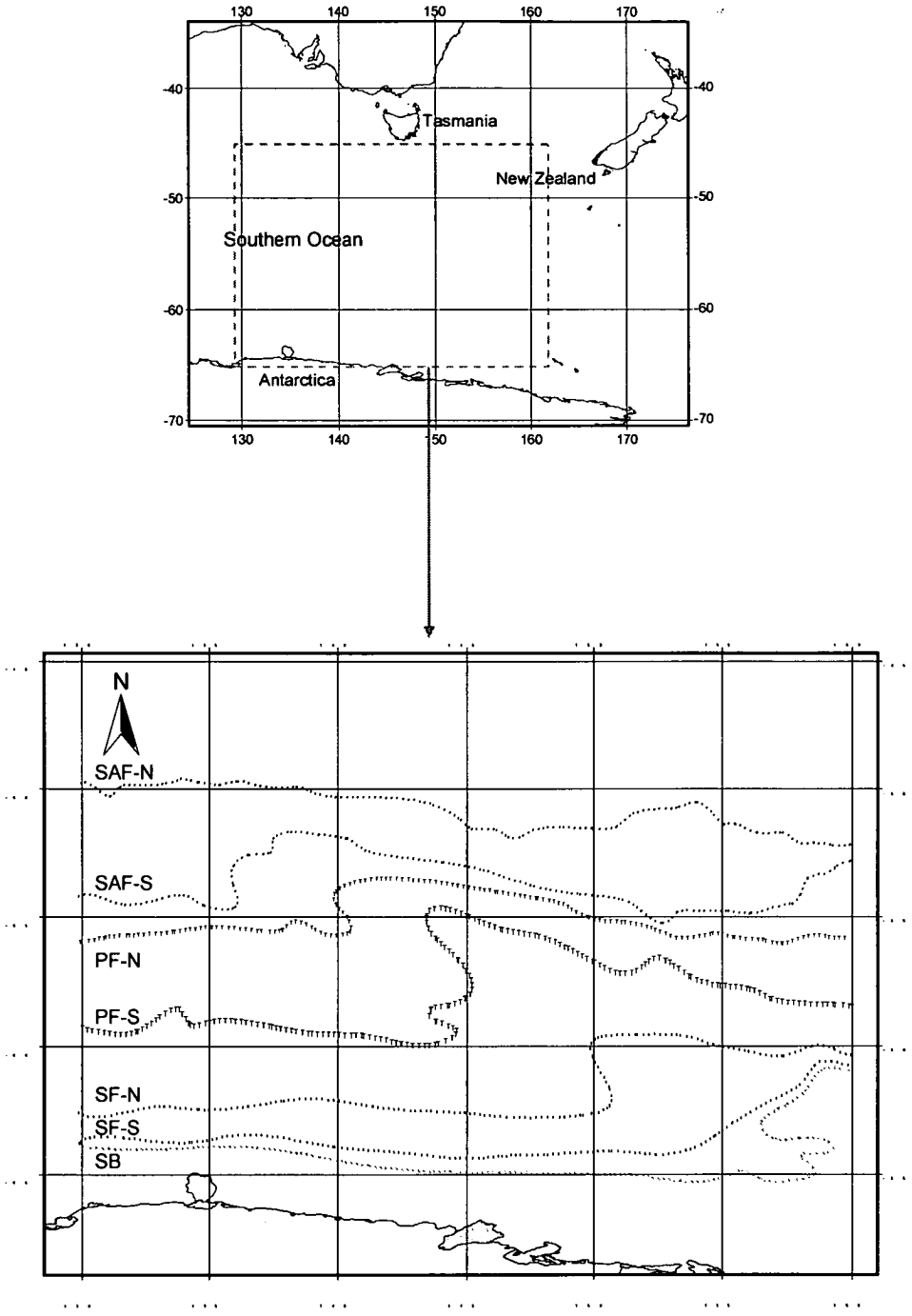


Figure 2.3. Location of fronts defined by Sokolov and Rintoul (2002) in the Southern Ocean South of Australia.

Table 2.1. The defining characteristics of oceanographic fronts identified along the 140°E meridian in the Antarctic Circumpolar Current south of Australia. Temperature and salinity characteristics used to define fronts from vertical profiles were taken from: 1. Orsi et al. 1995; 2. Sokolov and Rintoul 2002; 3. Belkin and Gordon 1996. Average surface positions along 140°E and average the Sea Surface Temperature at these locations were taken from Sokolov and Rintoul 2002.

Front	**Abbreviation**	**Temperature**	**Salinity**	**Average surface Position (2)**	**SST at average surface position**
Sub-Tropical Front	**STF**	>11°C (1)	> 34.9 (1)		13.5-11.0°C
Sub-Antarctic Front (north)	**SAF-N**	> 8°C to < 6°C at 300-400m (2)	34.3 at 200m (3)	-50.25°S	9.5-8.0°C
Sub-Antarctic Front (south)	**SAF-S**	> 6 °C to < 4°C at 300-400m (2)		-51.80 °S	7.5-5.5°C
Polar Front (north)	**PF-N**	2°C at 200m (1,2,3)		-55.72 °S	6.0-4.5°C
Polar Front (south)	**PF-S**	> 2.2°C in θ_{max} (2)		-59.54 °S	2.75-1.75°C
Southern Front (north)	**SF-N**	southern limit of θ_{max} > 2°C (2)		-62.12 °S	2.0-0.5°C
Southern Front (south)	**SF-S**	θ_{max} 1.8°C at 500m (1)	S_{max}34.73 at >800m (1)	-63.93 °S	1.25-0.25°C
Southern Boundary	**SB**	>1.5°C in θ_{max} (2)		-64.41 °S	

to other sectors of the Southern Ocean (sea surface temperature changing from ~ 13.5°C to 11.5°C across this front, as opposed to ~ 17°C to 12°C south of Africa). Given the regional specificity of Sokolov and Rintoul's (2002) study I have primarily used their definitions of frontal structure. Below I provide a brief description of the definition of these fronts, in the context of those given by Orsi et al. (1995).

The northern branch of the SAF (SAF-N) coincides with a decrease in temperature from > 8°C to < 6°C at 300-400m, and thus corresponds with the definition of the SAF by Orsi et al. (1995) and Belkin and Gordon (1996). The southern branch of the SAF (SAF-S) coincides with a decrease in temperature from > 6 °C to < 4°C at 300-400m. The northern branch of the PF (PF-N) corresponds with the definition of the PF given by Orsi et al. (1995) and Belkin and Gordon (1996), while the southern branch of the PF (PF-S) corresponds with the southernmost extent of water warmer than 2.2°C in the θ_{max} layer. The northern branch of the SF (SF-N) is defined by the southern limit of θ_{max} water warmer than 2°C. The definition of the southern branch of the SF (SF-S) corresponds with Orsi et al.'s (1995) definition of the SF. All branches of the SAF, PF and SF were regions of enhanced current velocity and were deep reaching features.

The definition of the SB by Sokolov and Rintoul followed Orsi et al. (1995), being the southern limit of the oxygen minimum associated with UCDW. Along 140°E this feature is coincident with the southern limit of water warmer than 1.5°C in the θ_{max} layer. The final front identified by Sokolov and Rintoul (2002) along 140°E is the Antarctic Slope Front (ASF). The ASF is characterised by the deepening towards the south of isotherms and isohalines. A summary of the features used for defining the Southern Ocean fronts south of Australia (along 140°E) is presented in Table 2.1. In addition Table 2.1 presents the average surface positions of fronts along 140°E, determined by satellite altimetry, and average the Sea Surface Temperature at these locations (Sokolov and Rintoul 2002).

2.2.3. Identification of fronts

During this study, underway Sea Surface Temperature (SST) and Surface Salinity (SS) data were typically collected with each tow. Surface data were used in conjunction with the average locations calculated by Sokolov and Rintoul (2002) to determine frontal positions on each CPR transect. CTD data aided the interpretation

of the study area's oceanographic structure, but were not collected on every voyage. Where CTD data were collected, vertical temperature and salinity profiles were generated for the upper 1000m of the water column using the contouring software SURFER 7.0. In all cases contouring was performed using the kriging technique. The details of environmental data collection are presented in the methods section of each chapter.

2.3. Zooplankton Collection

All CPR samples were collected using a Type II Mark V CPR (Figure 2.4). This model was based on the CPRs used in the SAHFOS survey but redesigned for easier unloading and loading of sampling mesh and preservative, and constructed from marine grade 316 steel (Hosie et al. 2003). The mesh diameter used during all tows was 270μm, the same used by the SAHFOS CPR survey (Reid et al. 2003), and the CPR was towed at a distance of 100m behind the vessel.

2.3.1. Workings of the Continuous Plankton Recorder

The design and workings of the CPR were described in detail by Hardy (1936a, 1939), and subsequently by numerous other authors (Batten et al. 2003, Reid et al. 2003). A summary is given here. The CPR consists of two main parts, an outer body and an internal removable cassette. The outer body is rectangular in shape but has a hydrodynamic nose cone with a small opening of 1.6cm^2, and a tapered tail with a large exhaust opening. The tail section has a box shaped fin (Figure 2.4) which gives the CPR stability at speeds of up to 20 knots (Batten et al. 2003), and an averaging towing depth of 6.7m (Hays and Warner 1993). A towing eye is located on the upper surface behind the nose cone. A propeller linked to a gearbox is fitted in the roof of the box section at the rear of the body.

The internal cassette is harnessed with three spools: 1. a lower spool with collecting net, 2. an upper spool with covering net and 3. a storage spool. When the cassette is fitted inside the outer body, the gearbox engages with cogs on the cassette so that during a tow the spinning propeller causes rotation of the storage spool. Thus while towing the preloaded collecting net and covering net are steadily drawn through the internal mechanism and onto the storage spool. The cassette has a through-passage so that when inserted there is continuous flow of water through the

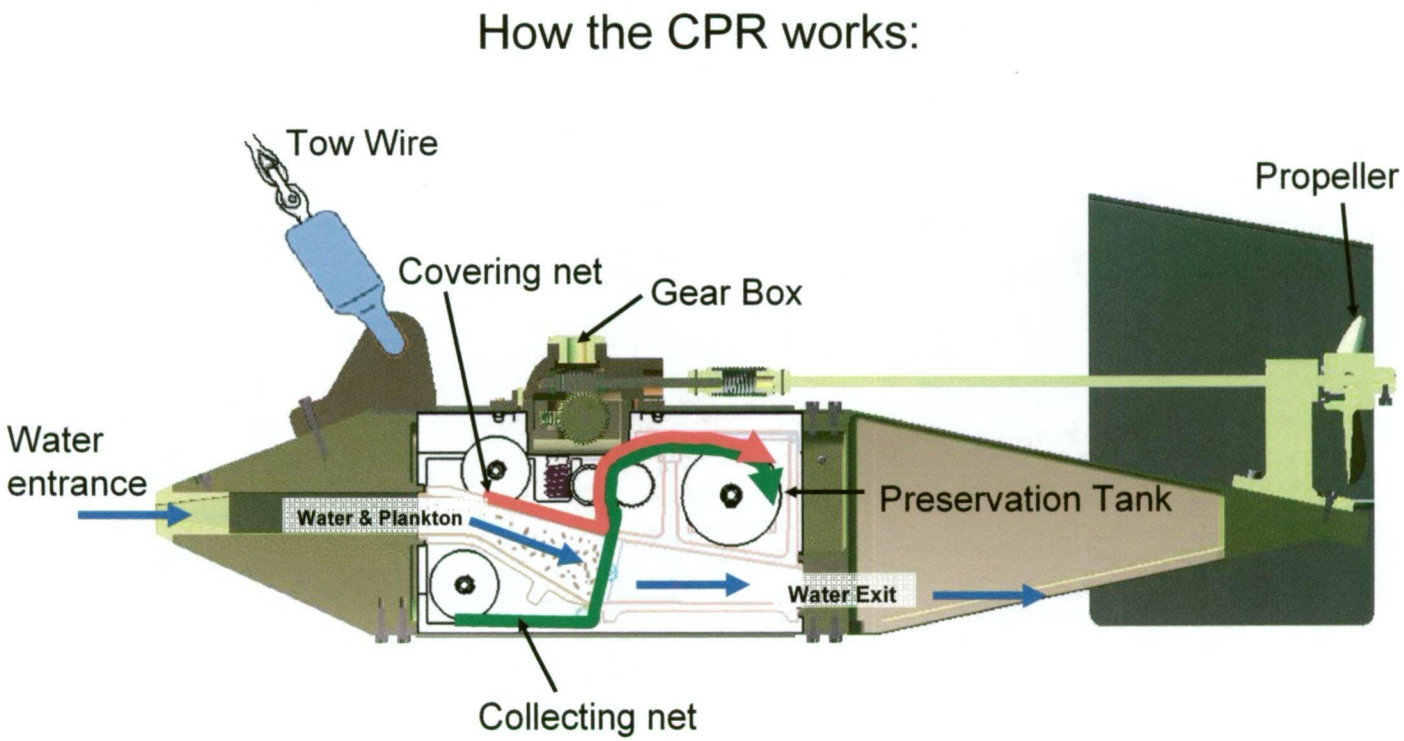


Figure 2.4. Transverse section of a Continuous Plankton Recorder illustrating its operation on deployment.

CPR. Behind the nose cone opening the CPR through-passage increases in size so that the size of the filtering area relative to the nose opening is 29:1. This effectively reduces the speed at which plankton come into contact with the collecting net (at 15 knots water flows through the filtering net at 0.5 knots) and minimises clogging by filtered plankton.

The collecting net is continuously pulled across the through passage in proportion to the speed of the ship, so that 5 cm of mesh is approximately equal to 5 nm of tow through the water. Subsequently the collecting net is 'sandwiched' by the covering net, fixing the position of the filtered animals. The mesh 'sandwich' is then wound onto the storage spool in a tank containing formaldehyde for preservation. A fusee mechanism ensures a steady tension is maintained throughout the spooling process and also compensates for the increasing diameter of the storage spool during the tow. Guide rollers with greater diameters at each end compress the edges of the mesh holding the sample, but not the central section onto which the majority of plankton are deposited.

Alister Hardy summed up the working of the CPR by analogy with the feeding of Amphioxus (Figure 2.5):

"*To sum up, the general principle of the mechanism may be compared with that used by the animal Amphioxus (Branchiostoma). The machine has a small opening leading into a larger cavity with an enlarged filtering surface. The size of the entrance can be adjusted and in the first machine, where it is larger than in later ones, there was a grid-work to keep out large objects. Instead of the plankton sieved out being carried off the "netting" by streams of mucous from the endostyle, the netting itself is made to move and carry the plankton with it. Just as the mucous collected in the epibranchial groove of Amphioxus carries the planktonic food in a continuous stream towards the oesophagus, so the gauze bandings carry the plankton continuously towards the storage chamber. Into this chamber is secreted, by narrow ducts from a "gland-like organ", a fluid preservative instead of digestive. Only recently have I realised that my "invention" is but an imitation of Nature's mechanism.*"

- Hardy 1936a, page 464 paragraph 2

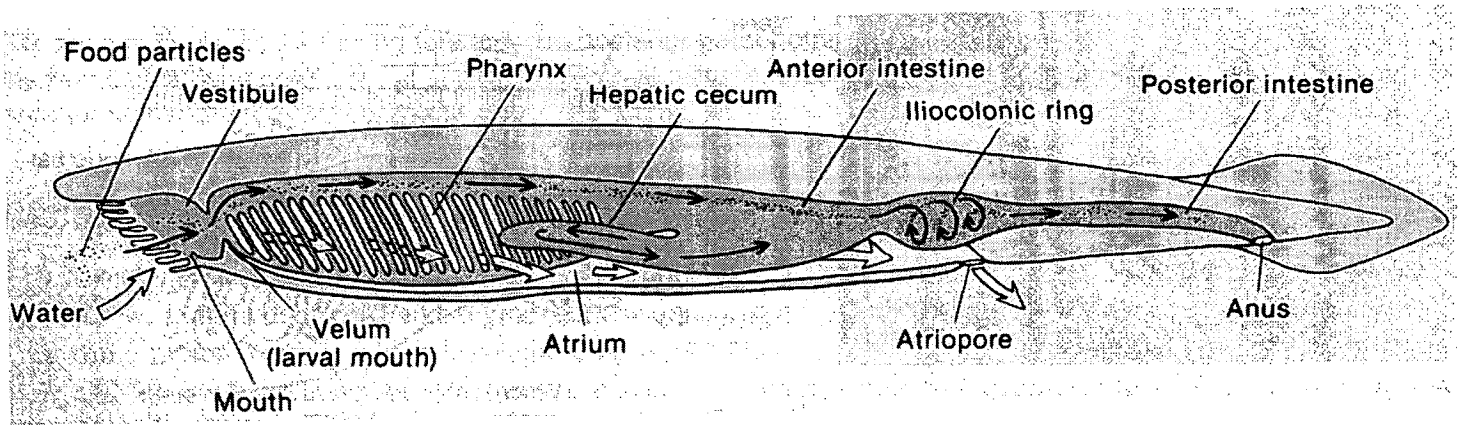


Figure 2.5. Transverse section of the Cephalochordate *Branchiostoma caribaeum* (amphioxus) illustrating its feeding, and the functional organisation of its digestive system. Open arrows show the passage of water, while the small closed arrows show the path of food particles and digestive enzymes. A full description of the feeding of amphioxus is provided in Section 2.3.1, following Hardy (1936a, page 464 paragraph 2). Figure taken from Ruppert and Barnes 1994, page 904).

2.3.2. CPR sample collection and processing

Prior to deployment from the towing vessel, the starting position of the mesh roll was marked with a permanent marker at the point where it entered the preservation bath, using the bath lid as a ruler. The deployment time was recorded in the towing log as the CPR entered the water. As a standard protocol the CPR is towed at a distance of ~ 100 m behind the vessel. Both the filtering and covering mesh are five meters long enabling a tow of ~ 450 nautical miles (nm) before retrieval. On retrieval the end-time was recorded in the towing log as the CPR exited the water. The finish position of the mesh was marked in the same way as the start position. If another tow was to be completed a new cassette was inserted into the outside body and the CPR immediately redeployed following the above protocol. The entire net on the used cassette was then unrolled and removed from the storage spindle, ensuring that the zooplankton side of the sampling net, and the covering layer are facing into each other. The net was then re-rolled, secured with elastic bands and stored in a 2*l* sample jar containing seawater and 4% borax buffered formaldehyde.

In the laboratory the mesh was soaked in particle free seawater for two days prior to processing in order to dilute or remove excess formaldehyde. The mesh was then cut into sections each representing a 5 nm sample along the length of a tow. The length (in centimetres) and number of 5nm sections to be cut from each mesh were calculated using a computer programme written in Visual Basic, based on the start and finish times recorded in the towing log and the length of the used mesh measured between the start and finish marks. This programme also enabled time stamped environmental data collected on board the towing vessel to be assembled into 5 nm data sections corresponding with each 5 nm mesh segment. As there was some variation in the environmental data collected for each tow used in this study, the details of these data are presented separately in each results chapter.

2.3.3. Zooplankton Identification

The plankton from each 5 nm sample were washed into a Bogorov sorting tray and investigated using a stereo dissecting microscope. In general the entire contents was identified and enumerated. However, some of the high density summer samples were sub-sampled and this is indicated in the methods section for each

chapter. Sub-sampling was conducted using a box-splitter (Omori and Ikeda 1984). Identification was to species level wherever possible for most taxonomic groups and, in addition, I attempted to identify the life stages of all copepods and euphausiids. Copepods were identified using the keys of (Razouls 1994, Guglielmo and Ianora 1995, Boltovskoy 1999b), and stages using Mauchline (1998). Euphausiids were identified using the keys of Kirkwood (1982), Baker et al. (1990), and Boltovskoy (1999b), and stages using Kirkwood (1982) and Boltovskoy (1999a,b). All other taxonomic groups were identified using O'Sullivan (1982a,b,c), Kirkwood (1983), Guglielmo and Ianora (1997), Boltovskoy (1999a,b).

Foraminifera, Ostracoda and Appendicularia were not identified to species and so abundance levels referred to these groups as a whole. Gelatinous and other soft bodied taxa were generally damaged when sandwiched between the two mesh layers, hindering identification. These types of plankton were therefore grouped as hydromedusae, ctenophores and siphonophores. *Salpa thompsoni* remained identifiable. Some *Tomopteris* spp. were identifiable to species level, however, as the majority were not, all specimens were grouped at the genus level. Chaetognaths were identified to species in Chapter 3, for comparison with vertical net samples. However, due to the difficulty in identifying them, and their generally low abundance levels in the CPR samples, they were grouped as Chaetognatha in subsequent chapters. Pteropod shells were frequently crushed on collection. As shell morphology is the most important feature for the identification of *Limacina* spp. no attempt was made to differentiate between species in this genus. Furthermore, only *Limacina* spp. bodies were counted, not shell fragments. A full species list is presented in Appendix 2.

2.4. Analysis

Prior to analysis, species abundance levels were converted to individuals.m^{-3}. This was done assuming 100 % filtration efficiency, giving a volume filtered of 1.5 m^3 / 5 nm. Customised electromagnetic flow meters have been designed for use on SAHFOS CPRs for experimental purposes, however, these flowmeters are incompatible with the CPRs employed by the Southern Ocean survey. Data gathered using these flowmeters have demonstrated that the average volume filtered by CPRs is actually slightly higher than expected (1.56 m^3 / 5nm) (Batten et al. 2003). Assuming 100 % filtration efficiency may therefore under-estimate zooplankton

densities by 4 %. An additional factor effecting observed densities is that of mesh clogging at high zooplankton densities. At the highest phytoplankton / zooplankton densities volume filtered was reduced by ~ 20 % (John et al. 2002). Therefore, by assuming 100 % filtration efficiency the abundance levels of zooplankton in this study were increasingly underestimated as their densities increased.

All analysis was performed using STATISTICA 6.0 for Windows. Analytical details are presented separately for each chapter.

Chapter 3

The Continuous Plankton Recorder in the Southern Ocean: sampling characteristics in relation to vertical net hauls

3.1. Introduction

In accordance with the first principles of monitoring, this chapter investigates the sampling characteristics of the CPR in the Southern Ocean. I set out to do this by direct comparison with vertical net hauls. Zooplankton have been quite extensively studied in the Southern Ocean using vertically and obliquely towed net systems, providing insights into population cycles (Ward et al. 1996, Atkinson 1998), community structure (Hopkins et al. 1993, Hosie 1994, Siegel and Harm 1996), vertical distributions (Piatkowski 1985) and biogeography (Pakhomov and McQuaid 1996, Errhif et al. 1997, Gibbons 1997). Comparison with vertical nets will therefore place the data collected by the CPR within the framework of existing data, as well as future studies where the application of vertical and obliquely towed nets is likely to remain prevalent.

The CPR differs fundamentally from vertically and obliquely towed net systems in that it samples plankton in the horizontal plane. In addition, the CPR only samples plankton in the surface waters, the SAHFOS CPRs having a mean operational depth of 6.7m (Hays and Warner 1993). Conversely, vertically and obliquely towed nets generally sample to depths > 200m (e.g. Schnack-Schiel and Mujica 1994, Errhif et al. 1997, Atkinson and Sinclair 2000). It is well established that the depth distribution of Southern Ocean zooplankton varies on both temporal (diel and seasonal) and spatial scales (e.g. Voronina et al. 1978, Ward et al. 1995, Atkinson 1998, Schnack-Schiel et al. 1998, Atkinson and Sinclair 2000). Vertical zooplankton dynamics are therefore of great relevance to the Southern Ocean CPR survey, and may impact significantly on the CPR data sets. Apart from sampling depth, structural (e.g. mouth area) and operational characteristics (e.g. towing speed) of CPR and traditional net systems are also likely to result in sampling differences.

Vertically and obliquely towed nets in the Indian (Errhif et al. 1997) and Atlantic (Tarling et al. 1995, Pakhomov et al. 2000) sectors of the Southern Ocean have demonstrated that zooplankton communities have distinct latitudinal patterns in species composition and community structure, reflecting the strong physical

zonation across circumpolar frontal systems (Deacon 1982, Orsi et al. 1995). The communities associated with biogeographic zones are important indicators of physical conditions, and consequently environmental change. For long-term monitoring purposes it is therefore essential that the sampling resolution of the CPR be sufficient to separate different biogeographic zones.
This chapter aimed to:

1. Investigate the sampling characteristics of the CPR by direct comparison with vertical nets, paying particular attention to the influence of vertical distribution
2. Investigate the ability of the CPR to identify horizontal biogeographic patterns in zooplankton community structure

The results of Chapter 3 have, in part, been published as Hunt and Hosie (2003).

3.2. Materials and Methods

3.2.1. Data collection

Data were collected in November and December 2001 aboard the RV *Aurora Australis*. A repeat transect was run south of Tasmania, along approximately 140°E, providing the unique opportunity to compare vertical nets and CPR (Type II Mark V) samples from the same transect line (Figure 3.1).

Oceanographic stations were conducted at regular intervals (every 20' to 1° latitude) on the southern leg of the voyage which involved the deployment of a General Oceanics Mark IIIC CTD (Figure 3.2). All CTD stations used in this analysis were conducted to the sea floor but only the upper 1000m is presented. Temperature and pressure sensors were calibrated at CSIRO Marine Laboratories, Hobart, in October 2001, and conductivity was calibrated *in situ* using Niskin bottle samples.

Vertical net hauls were completed at nineteen of the oceanographic stations from 9-22 November (Figure 3.1). Four depth zones were sampled at each station, 0-20m, 20-50m, 50-100m, and 100-150m, using NORPAC nets with a mouth diameter of 45cm and fitted with 270μm nylon mesh (the same mesh size used in the CPR survey). A mechanical revolution counting flowmeter (Rigosha and Co., Ltd, no.

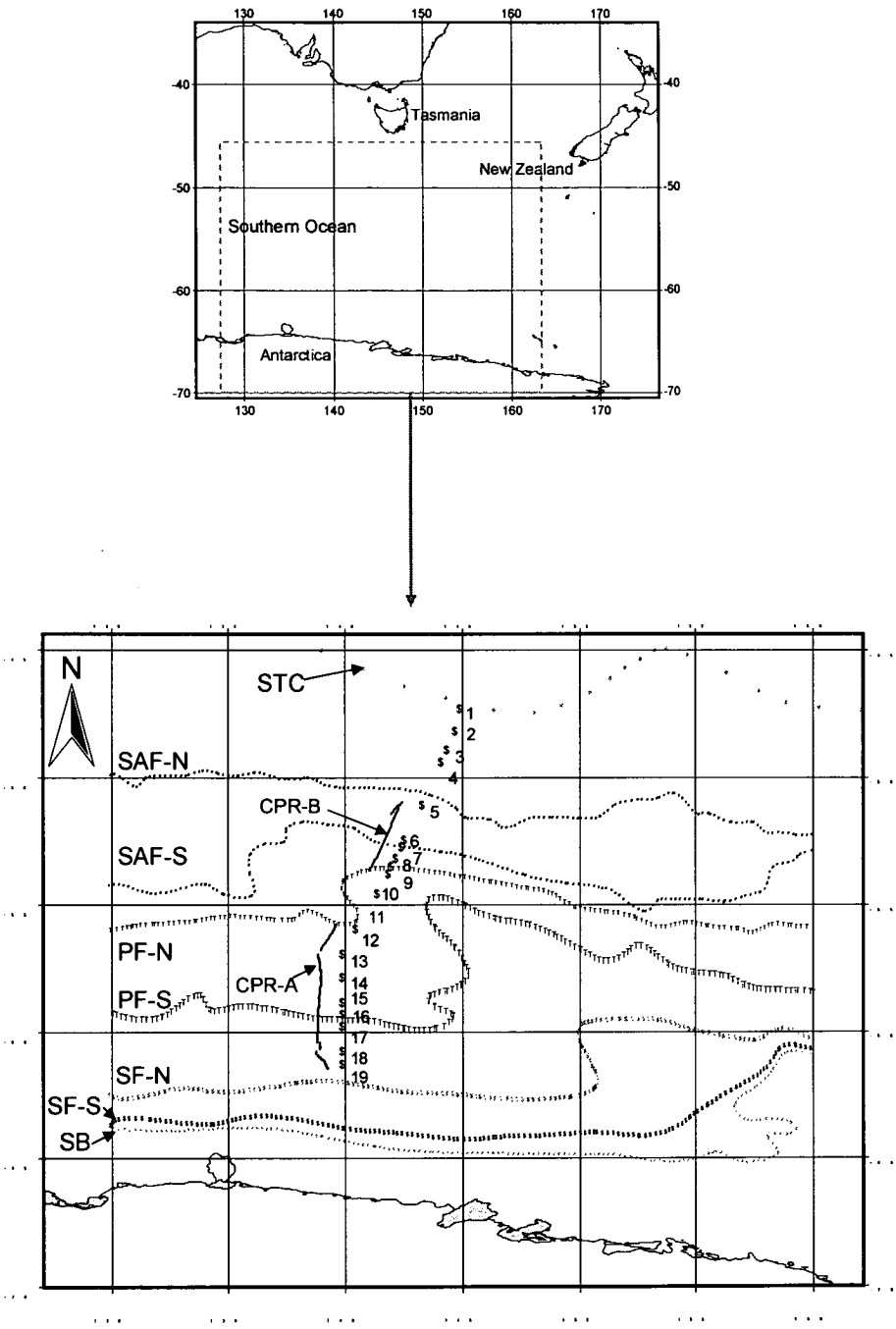


Figure 3.1. Map of study area showing the average positions of major frontal systems south of Tasmania. The position of the STC is that of Orsi et al. (1995), while the positions of all other fronts are those of Sokolov and Rintoul (2002). CPR tows A and B are labeled and NORPAC tows, completed at CTD stations, are indicated by numbered ▲'s.

5571-A) was secured across the mouth of the net for volume filtered calculation.

Two CPR tows were completed from 7-11 December, the first (A) between 61.60°S and 55.74°S (355nm) and the second (B) between 53.62°S and 50.85°S (207 nm) (Figure 3.1). During Tow A the CPR was twice removed for CTD stations but was redeployed at the same positions, and so these stations did not affect the spatial continuity of the transect. Transect B sampled the section 51.29°S to 50.85°S twice due to the vessel doubling back for a CTD station. No flow meter was attached to the CPR and so filtration efficiency was assumed to be 100% (Section 2.4). The towing depth was calculated using the power equation:

$$y = 209.13x^{-1.1921}$$

where x is GPS derived speed over ground in knots. This equation was calculated from data collected on Voyage 4 of the RV *Aurora Australis* during the 2002/03 field season. A model Mk5 Wildlife Computers microprocessor-controlled Time-Depth Recorder (TDR) was attached to the CPR, recording depth at 1 minute intervals during all sampling runs. The time stamped depth data was subsequently plotted against GPS speed over ground which was also recorded at 1 minute intervals.

CPR sample treatment and processing followed the protocol in Section 2.3.2. The entire contents of each 5nm CPR sample was identified and enumerated, while the NORPAC samples were sub-sampled using a box splitter, aliquots ranging between 1/2 and 1/16 of the whole (following Omori and Ikeda 1984). Identification was to species and stage level wherever possible and followed the protocol in Section 2.3.3. *Thysanoessa macrura* and *Thysanoessa vicina* have overlapping ranges and are morphologically very similar, the only reliable difference being in the petasma of the males, and consequently were merged as *Thysanoessa macrura / vicina* (Kirkwood 1982). Zooplankton abundance was converted to individuals.m^{-3}.

Throughout the voyage sea surface temperature, salinity and PAR (photosynthetically active radiation) were logged at 1 minute intervals by shipboard meters. Temperature was measured by a Yokagawa digital thermometer (model 7563) with a resolution of 0.01°C and accuracy ~ 0.07°C. The thermometer was located 20mm inside the uncontaminated seawater inlet in the bow of the ship at ~ 7.5m depth. Salinity was measured using a Sea Bird Electronics (model SBE-21)

thermosalinograph and measured from the uncontaminated seawater line. PAR ($\mu mol.s^{-1}.m^{-2}$) was measured with a LI-190SZ Quantum Sensor located on top of the main mast, 31.2m above sea level.

3.2.2. Data Analysis

3.2.2.1. Direct comparison of CPR and vertical nets

For the purpose of direct comparison between the CPR and vertical nets, a sub-set of NORPAC samples was used comprising those stations within the latitudinal range sampled by the CPR (i.e. excluding the northerly NORPAC stations 1 to 4). From this spatially congruent sub-set five sample groups were produced by grouping all CPR samples, and NORPAC samples for each depth zone. This had the effect of integrating latitudinal and diel variation, and focusing the analysis on depth and net related differences in plankton community structure. Four community indices were calculated for each individual CPR and NORPAC sample, and subsequently averaged for each of the five sample groupings. These indices included species richness (r), Shannon-Weaver diversity index (H'), Pielou's evenness coefficient (J'), and Dominance (D).

$$H' = \sum_{i=1}^{S} p_i . \log_2 p_i$$

Where S is the total number of species and p_i is the proportion of the number of individuals of species i to the total number of individuals.

$$J' = \frac{H'}{H'\max} = \frac{H'}{\log_2 S}$$

where *H'max* refers to the theoretical distribution in which all species are equally represented. When *J'* is high, the difference between the number of individuals per species is small.

$$D = 100\frac{n1 + n2}{N}$$

where *n1* and *n2* are the number of individuals of the dominant species and N is the total number of individuals. Spearman rank-order correlation was used to investigate the relationship between species richness, diversity, evenness, and dominance.

The total species list for all samples included a number of rare, low abundance taxa. In order to compare the species abundance levels between nets and

depth zones the total number of species was reduced to a subset comprising those species occurring in > 4 samples in any of the 5 sample groups. The subset contained 30 taxa, including 27 species and 3 higher taxonomic groups. The abundance data for these 30 taxa was $\log_{10}(x+1)$ transformed, and an ANOVA performed to test the hypothesis that the abundance levels of taxa did not differ between sample groups. Where significant differences were detected a Newman-Keuls multiple range test was run to identify inter-group differences.

3.2.2.2. Spatial distribution of communities: Multivariate Analysis of Community Structure

Two sample by taxon matrices were generated, one for the CPR samples and the other for the complete NORPAC sample set (all depth zones), using zooplankton abundance data expressed as individuals.m^{-3}. Copepodite stages C1 to C3 of *Calanus simillimus* and *C. propinquus*, *Calanoides acutus* and *Neocalanus tonsus* could not always be identified to species level and consequently, together with unidentified nauplii, were excluded from the analysis. The stages of other taxa were merged for the analysis. The CPR and NORPAC data matrices were then analysed separately using the combination of a classification and an ordination technique.

The classification technique used was that of Hierarchical Cluster Analysis. Prior to clustering, the species abundance data were transformed using the $\log_{10}(x+1)$ function. This transformation had the effect of scaling down the scores of highly abundant species while increasing the contribution of species occurring at low abundance (Field et al. 1982). Inter-sample relatedness (q-type analysis) of the log-transformed data matrix was determined using the Bray-Curtis dissimilarity index (Bray and Curtis 1957):

$$\delta_{jk} = \frac{\sum_{i=1}^{s} |Y_{ij} - Y_{ik}|}{\sum_{i=1}^{s} |Y_{ij} + Y_{ik}|}$$

where Y_{ij} is the score for the ith species in the jth sample; Y_{ik} is the score for the ith species in the kth sample; δ_{jk} is the dissimilarity between the jth and kth samples summed for all s species. The Bray-Curtis measure of dissimilarity is not affected by joint absences in the sample by species matrix (Field et al. 1982), an unavoidable

feature of plankton data sets. In addition, when comparing samples it gives greater weighting to more abundant species. The triangular dissimilarity matrix was subsequently arranged into clusters using Un-Weighted Pair Group Average Linkage. This linkage method joins two groups of samples at the average level of similarity between all members of one group with all members of the other group (Field et al. 1982).

Cluster analyses tend to over-emphasize discontinuities and consequently can force graded series into discrete classes (Field et al. 1982). Ordination techniques are therefore a good compliment to clustering as they emphasise gradients (Gauch 1982). The ordination technique used in this thesis was that of Correspondence Analysis (CoA). Computationally CoA is an eigenanalysis related to Principal Component Analysis (PCA) (Gauch 1982), which partitions the chi-square statistic describing a contingency table into a hierarchy of contributing variance components or factors (Ortner et al. 1989). In this instance the contingency table was the sample by species abundance data matrix. Correspondence Analysis can also be performed by weighted averaging, and consequently CoA is also known as Reciprocal Averaging (RA). Full computational details of CoA and RA are presented in Pielou (1984) and Legendre and Legendre (1998).

Correspondence Analysis is well suited to handling long community gradients. Employment of chi-square distances, rather than covariance or correlation as in PCA, gives CoA good properties for ordination, including tolerance of non-monotonic rise and fall of species scores (and thus the heterogenous nature of samples typical of ecological studies) (Gauch et al. 1977), and tolerance of missing data points (zeros) (Ortner et al. 1989). A unique feature of CoA is that it produces simultaneous q-type (samples) and r-type (species) ordinations which are approximately co-ordinate with each other (Gauch et al. 1977). As the relationship between samples / rows is quantified using the X^2 distance, CoA ordinations are a reflection of percentage abundance levels (Ortner et al. 1989).

Correspondence Analysis was performed on an un-transformed sample by species matrix. Transformation would have had the effect of altering the percent contribution of species to total abundance. Furthermore, as outliers have a potentially severe effect on CoA ordinations (Gauch et al. 1977), data sets were reduced to species occurring in > 4% of samples prior to ordination. Only the first two dimensions were displayed. Eigenvalues for each dimension were indicated on

the respective figures, as well as the proportion of overall inertia explained by that dimension. The species ordinations (r-type) were not presented in this chapter, and community composition is dealt with extensively in Chapter 4.

Gauch (1982) highlighted two important features of CoA ordination which are important for their interpretation. The first axis ends tend to be compressed relative to the middle and this means that a given distance of separation in the ordination does not specify a consistent meaning in terms of differences between samples (or species). Secondly, as a consequence of the end compression in the first axis and the second axis being a quadratic function of the first, the second axis may become arched. The first axis therefore mainly separates adjacent points in the axis middle while the second axis mainly separates adjacent points near the axis ends. However, together they produce a two-dimensional ordination with fairly even spacing between successive points. An outcome of the arch effect is that common / widespread species tend to concentrate in the middle of the ordination. Conversely, rare species and species occurring at low / high abundance are treated as being distinctive, becoming distributed on the periphery of the ordination (Gauch et al. 1977).

3.3. Results

3.3.1. Oceanography

Based on the frontal definitions in Table 2.1 the SAF-N was located at ~ 49°S and the SAF-S at ~ 51°S (Figure 3.2a,b). Sea Surface Temperature (SST) and Surface Salinity (SS) data measured during the CPR transect showed two strong temperature and salinity gradients, one at 49°-50°S and the other at 52°S representing the surface expressions of the SAF-N and the SAF-S respectively (Figure 3.3a,b). In the vertical profiles the PF-N was located at ~ 54.5°S, the PF-S at ~ 60.5°S, and the SF-N at ~ 61.5°S (Figure 3.2). These positions corresponded well with sharp SST gradients, indicating that the PF-N, PF-S and SF-N were identifiable in the surface profiles (Figure 3.3a). Surface Salinity remained relatively consistent between the PF-N and PF-S, however a sharp gradient in SS at ~ 61.5°S indicated the location of the SF-N (Figure 3.3a).

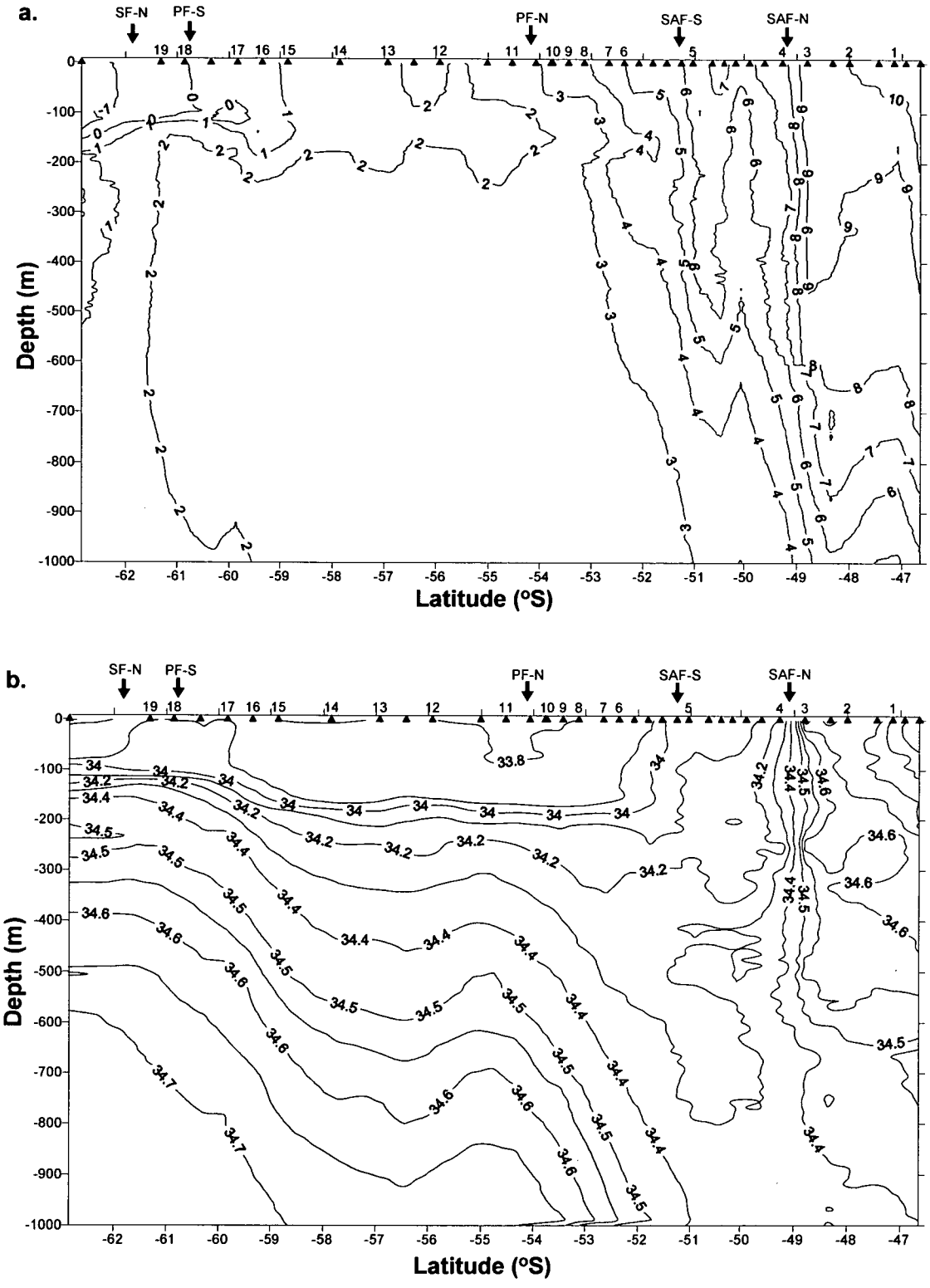


Figure 3.2. Vertical **a.** temperature and **b.** salinity profiles though 1000m from the southern leg of the 140°E transect. CTD stations are indicated along the top of each figure by ▲, and numbers correspond with stations where vertical NORPAC net hauls were conducted. The fontal systems indicated follow the definitions in Table 2.1. SAF-N - northern Sub-Antarctic Front; SAF-S - southern Sub-Antarctic Front; PF-N - northern Polar Front; PF-S - southern Polar Front, SF-N - northern Southern Front.

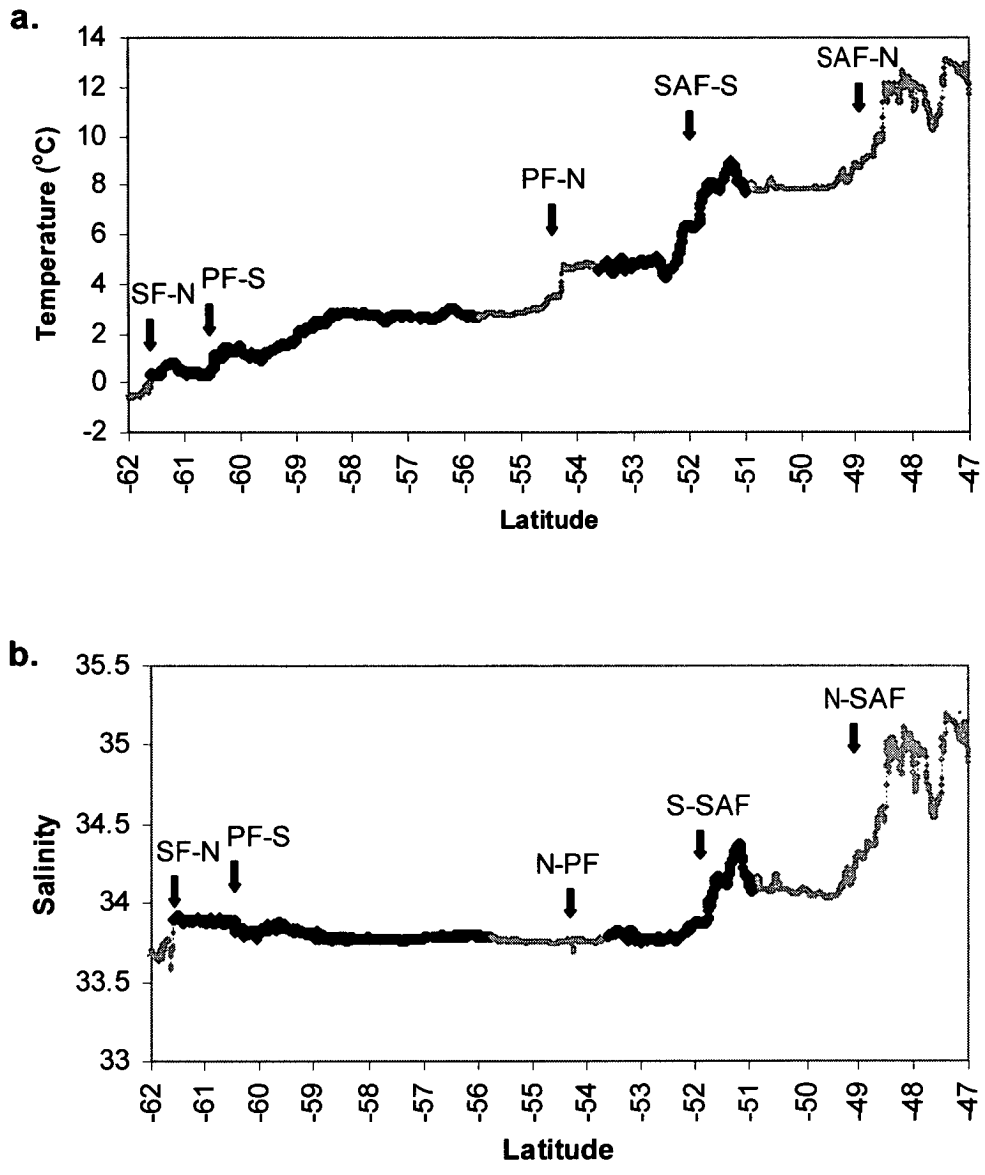


Figure 3.3. Underway sea surface **a.** temperature (°C) and **b.** salinity recorded during the northern leg of the voyage, in conjunction with the CPR tows. The positions of fronts, identified by surface features, are indicated. SAF-N - northern Sub-Antarctic Front; SAF-S - southern Sub-Antarctic Front; PF-N - northern Polar Front; PF-S - southern Polar Front, SF-N - northern Southern Front.

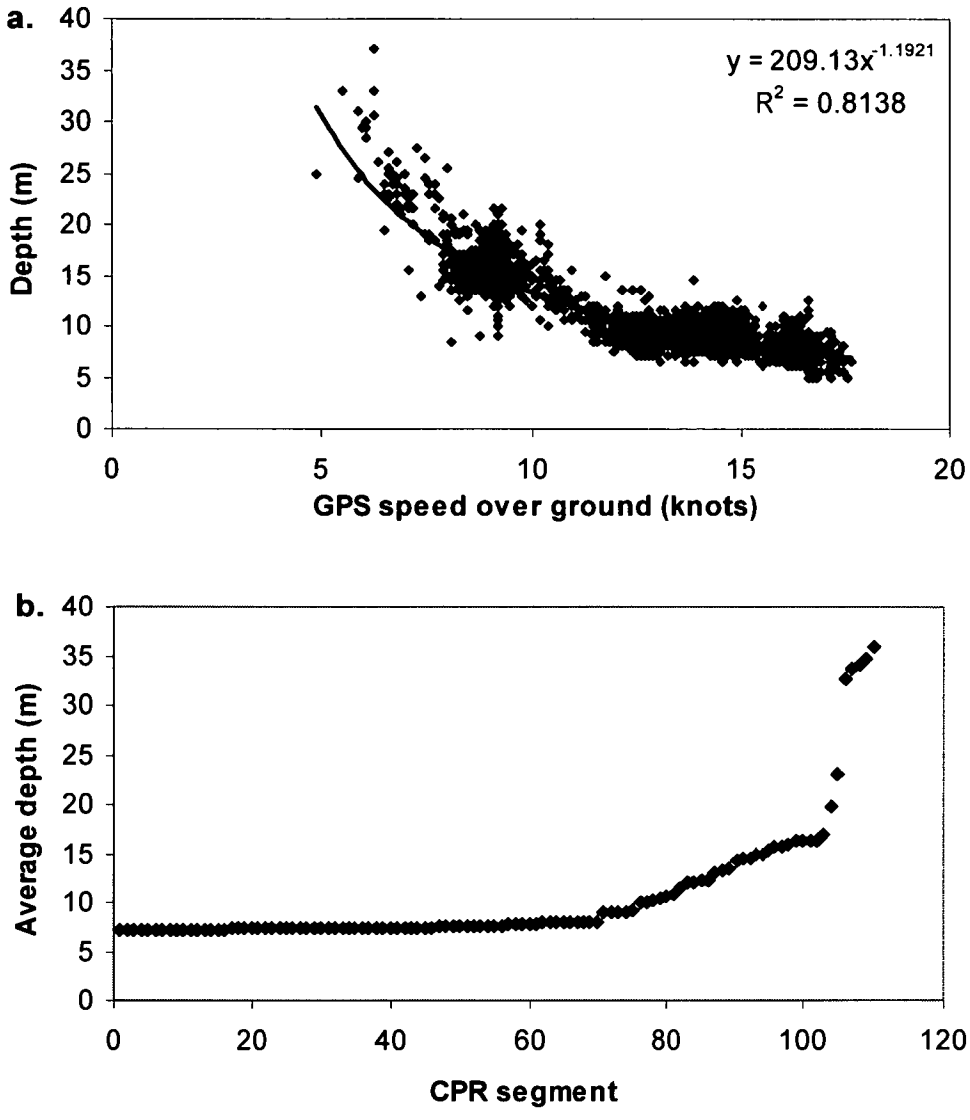


Figure 3.4. a. Relationship between CPR depth (m) and GPS speed over ground (knots), recorded during Voyage 4 of the 2002 / 2003 field season. The power equation describing the regression line and its R^2 value are indicated; **b.** average depth (m) of each 5nm CPR sample collected during the CPR-NORPAC comparative study, determined from the power equation in **a.**

3.3.2. CPR Sampling Depth

CPR depth was strongly correlated with ship speed for a set length of towing wire (Figure 3.4a). Average CPR sampling depth during the CPR-NORPAC comparative study was 10.5m (Figure 3.4b). The majority of sampling occurred at a depth of ~ 7.5m, corresponding with a mean ship speed of ~ 15 knots. Only 6 samples had a sampling depth of > 20m, and these occurred during the approach or departure from CTD stations when the vessel slowed down.

3.3.3. Zooplankton

A strong negative correlation between zooplankton abundance and PAR was evident for the CPR data (Figure 3.5a). Abundance levels recorded by the CPR were highest north of the Polar Front during both day and night. The pattern of diel variation was not as distinct for NORPAC stations, and the two stations with highest densities were sampled during the day (Figure 3.5b). However, when averaged across stations for each depth zone, it was clear that abundance was highest at low radiation levels (Figure 3.5c). There was little difference in abundance between the depth zones sampled by the NORPAC nets, although being slightly lower at night in the 0-20m zone. Average CPR densities were higher than those recorded in any of the depth zones sampled by the NORPAC nets, and the large standard deviations demonstrated that peak CPR sample densities reached substantially higher levels.

Average species richness (r) increased with depth and was lowest for the CPR samples (Figure 3.6a). The region between 20m and 100m had the largest diel flux in species richness indicating a strong influence of vertical migration. The total number of species identified in sample groups reflected average r, being lowest in the CPR samples and increasing with depth. Diversity (H') increased with depth while dominance (D) decreased with depth, indicative of the significant negative correlation between these two indices (Figure 3.6b,c; Table 3.1). Although higher H' and lower D were associated with more speciose communities, within the NORPAC depth groups H' and D were most strongly related to changes in the relative abundance of species rather than species richness itself (Table 3.1). Conversely, within the CPR samples H' and D were influenced by both species richness and the relative abundance of species. In the CPR and 0-20m samples H' increased

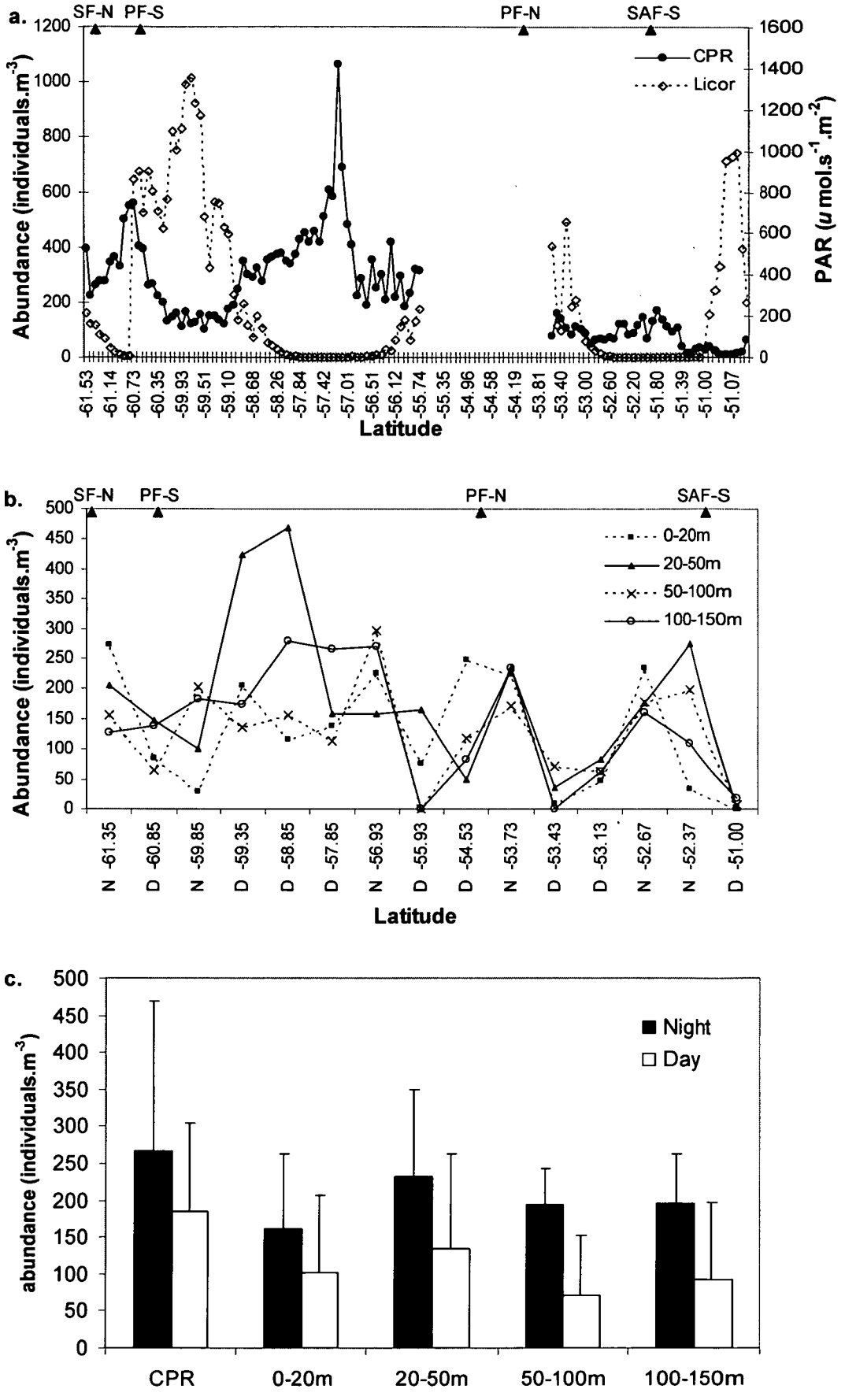


Figure 3.5. *legend overleaf...*

Figure 3.6. Average zooplankton abundance for **a.** CPR samples, plotted with PAR ($\mu mol.s^{-1}.m^{-2}$) and **b.** NORPAC samples (N - night, D – day) from each depth zone; **c.** day and night average abundance and standard deviations for CPR samples (n = 112) and each NORPAC depth zone (0-20m: n = 15; 20-50m: n = 15; 50-100m: n = 14; 100-150m: n = 13). Night was defined as PAR radiation < 100 $\mu mol.s^{-1}.m^{-2}$. The positions of fronts are indicated on **a** and **b** by ▲: SAF-S - southern Sub-Antarctic Front; PF-N - northern Polar Front; PF-S - southern Polar Front, SF-N - northern Southern Front.

Table 3.1. Spearman rank-order correlation coefficients between the community structure indices of species richness (r), Diversity (H'), Dominance (D) and Evenness (J). Significant correlations are underlined and in bold. n - number of samples.

	r-H'	r-D	r-J	H'-D	H'-J	J-D	n
CPR	**0.584**	**-0.283**	**-0.598**	**-0.831**	0.196	**-0.469**	112
0-20m	0.437	-0.304	-0.217	**-0.815**	**0.686**	**-0.611**	15
20-50m	0.505	0.098	-0.354	**-0.618**	0.469	**-0.917**	15
50-100m	-0.077	0.117	**-0.569**	**-0.912**	**0.819**	**-0.848**	14
100-150m	0.333	-0.323	-0.042	**-0.962**	**0.901**	**-0.887**	13

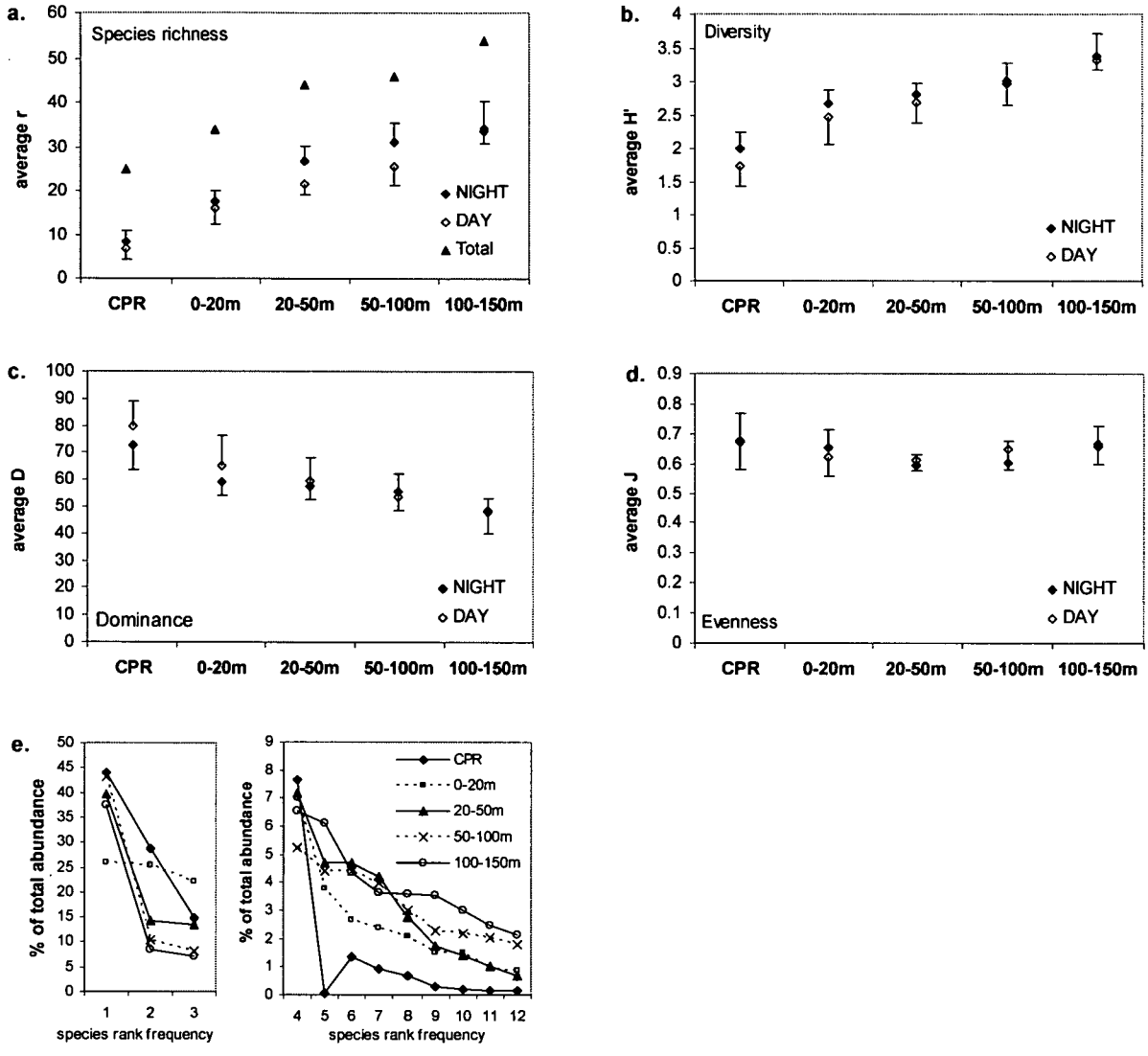


Figure 3.7. Average and standard deviation of **a.** species richness - r **b.** diversity – H' **c.** dominance – D **d.** evenness - J, and **e.** percentage contribution of the 12 dominant taxa to total abundance in CPR samples and the 4 NORPAC net depth zones (0-20m; 20-50m; 50-100m; 100-150m). In Figure 3.6a total species richness is indicated by ▲.

markedly at night and this was reflected by dominance (D) levels (Figure 3.6c). Evenness (E) was similar for all sample groups indicating a similar distribution pattern of individuals amongst species (Figure 3.6d). All sample groups were characterised by at least one species that made a disproportionately high contribution to total abundance (Figure 3.6e), while at the opposite end of the spectrum having rare and low abundance species. Within all sample groups J had a strong negative correlation with D (Table 3.1).

The species richness of all plankton groups, with the exception of chaetognaths, was lowest in the CPR samples (Figure 3.7). The majority of zooplankton groups showed an increase in species richness with depth, concurring with the overall pattern seen for the total population (Figure 3.6a). Copepods were by far the biggest contributor to total species richness in all depth zones.

Copepods and foraminifera dominated the CPR samples and all NORPAC depth zones, contributing between 72 % and 84 % to total abundance (Figure 3.8). Appendicularians made a large contribution to total densities in all sample groups, but particularly in CPR and 0-20m NORPAC samples where they were most abundant (Table 3.2). With the exception of pteropods, other zooplankton groups contributed little to total CPR abundance. By comparison, pteropods, euphausiids, hyperiids and chaetognaths were relatively important components of the community in NORPAC samples from the equivalent sampling depth (0-20m). Below 20m the contribution of appendicularians decreased while the contribution of other groups, including euphausiids, chaetognaths, polychaetes, fish and gelatinous plankton was proportionally larger.

The CPR samples were characterized by significantly higher densities of foraminifera, *O. similis* and appendicularians than NORPAC samples (Table 3.2). In the NORPAC samples both *O. similis* and appendicularians were most abundant in the 0-20m depth zone, and their abundance levels decreased with depth to their lowest levels in the 100-150m samples. The CPR samples had significantly higher densities of *Rhincalanus gigas* nauplii than NORPAC samples. However, *R. gigas* (copepodites and adults combined) abundance was low in the CPR samples and increased with depth to highest levels in the 100-150m samples. *Ctenocalanus citer* was a major contributor to total densities in all sample groups. *Thysanoessa macrura / vicina* occurred at lowest abundance in the CPR and 0-20m samples, and at significantly higher levels below 20m. The copepods *Aetidius armatus*, *Oncaea* sp.,

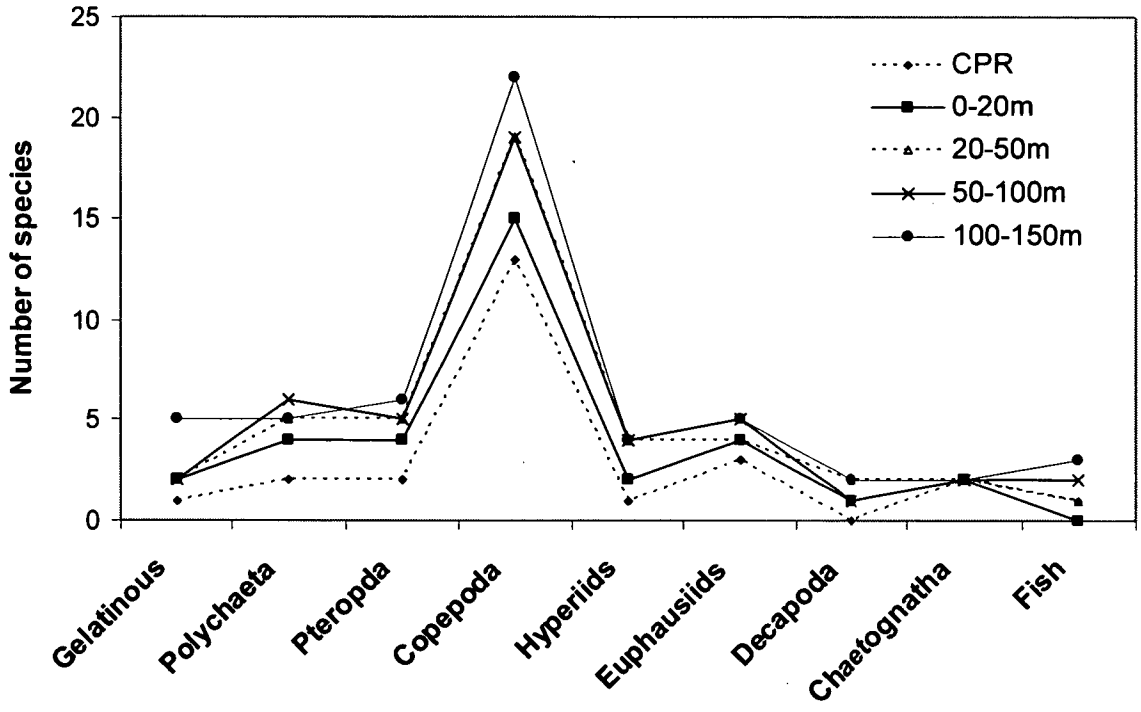


Figure 3.8. Species richness of major zooplankton groups for CPR samples and the 4 NORPAC net depth zones (0-20m; 20-50m; 50-100m; 100-150m).

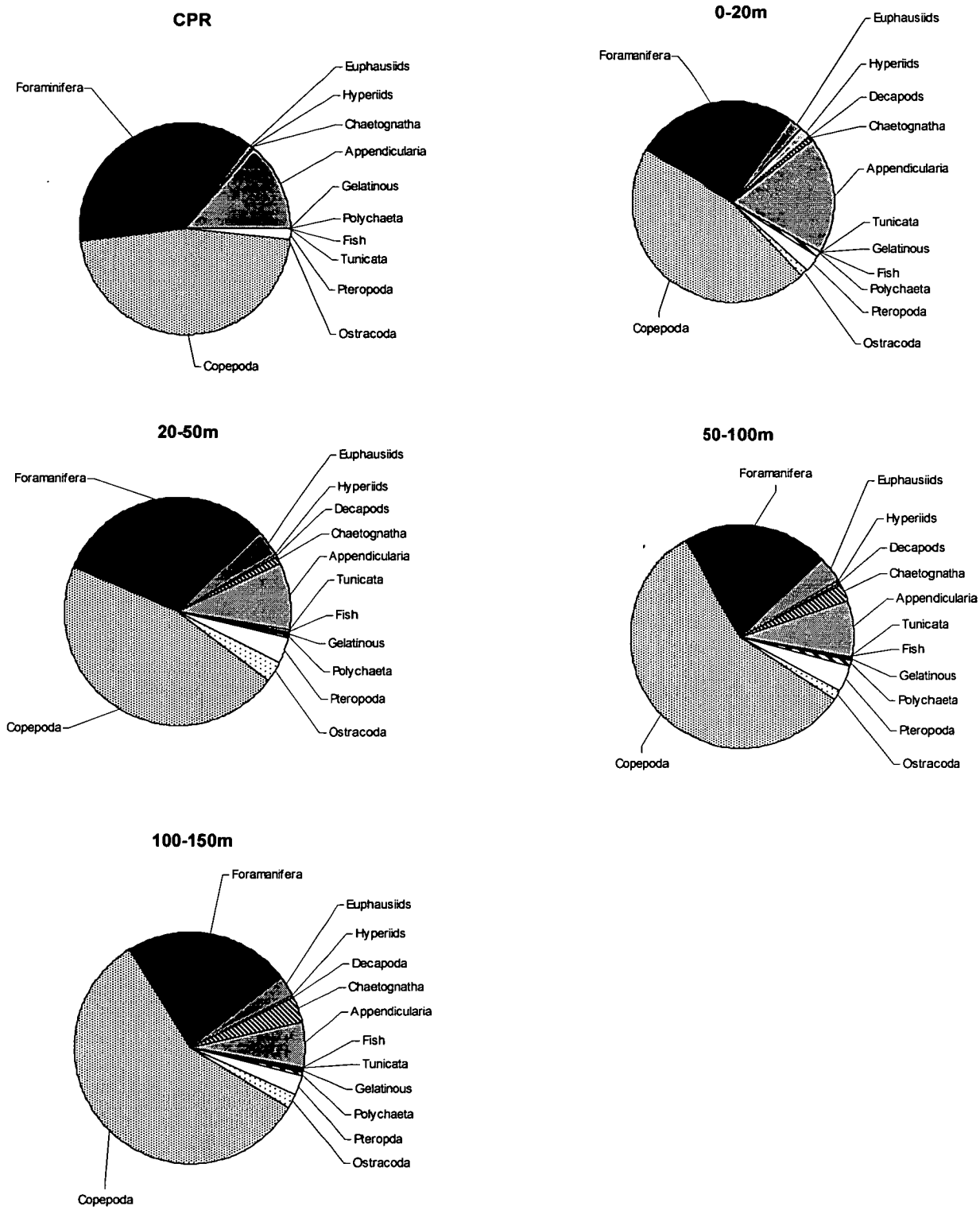


Figure 3.9. Percentage contribution of major zooplankton groups to total abundance in CPR samples and the 4 NORPAC net depth zones (0-20m; 20-50m; 50-100m; 100-150m).

Table 3.2. Abundance of zooplankton species occurring at > 4 samples in any of the 5 sample groups. P levels were determined by one-way ANOVA. Significant ($p < 0.005$) differences between sample groups were determined by Newman-Keuls multiple range tests and are indicated by different letters. Highest abundance levels are in bold and underlined. ns – not significant.

Taxon	p	Average Abundance (individuals.m^{-3})				
		CPR	20 m	20-50 m	50-100 m	100-150 m
Foraminifera	***	**y85.821**	x15.562	x25.348	x14.410	x18.088
Phalacrophorus pictus	ns	0.214	0.264	0.199	0.139	0.264
Clio pyrimidata antarctica	ns	0.125	0.018	0.074	0.335	0.353
Limacina spp.	ns	1.536	1.688	2.587	2.294	1.756
Spongiobranchea australis	***	x0.000	x0.000	**y0.032**	x0.010	**y0.032**
Ostracoda	***	x0.143	xy0.659	z2.552	yz0.929	y1.450
Aetidius armatus	***	x0.000	x0.000	x0.000	x0.000	**y0.056**
Calanoides acutus	***	x0.006	x0.069	x0.085	**y0.195**	**y0.219**
Calanus simillimus	***	x0.179	yz3.037	**z3.907**	yz2.718	y2.091
Clausocalanus brevipes	***	x0.304	xy0.658	xy0.956	**y1.126**	**y1.236**
Clausocalanus laticeps	ns	1.000	1.152	1.508	1.056	1.165
Ctenocalanus citer	ns	16.577	11.043	21.590	22.543	21.889
Eucalanus longiceps	***	x0.006	x0.021	x0.038	**y0.122**	**y0.176**
Haloptilus oxycephalus	***	x0.036	y0.201	yz0.370	zp0.536	**p0.549**
Metridia lucens	ns	0.077	0.263	0.070	0.139	0.271
Oithona frigida	***	x0.042	x0.109	x0.058	y0.946	**z3.573**
Oithona similis	***	**y49.244**	x9.652	x7.276	x4.276	x4.197
Oncaea sp.	***	x0.000	x0.062	x0.100	**y2.074**	**y4.236**
Rhincalanus gigas	***	x0.048	z0.377	yz0.321	p1.183	**q2.125**
R. gigas nauplii	***	**y8.423**	x0.066	x0.074	x0.026	x0.040
Scolecithricella minor	***	0.137	0.000	0.077	0.292	0.907
Themisto gaudichaudii	ns	0.185	0.903	0.158	0.219	0.115
Euphausia frigida	ns	0.131	0.035	0.036	0.105	0.133
Euphausia triacantha	***	x0.000	xy0.067	xy0.057	**y0.120**	xy0.061
Euphausia vallentini	ns	0.042	0.130	0.559	0.079	0.079
Thysanoessa macrura / vicina	***	x0.762	x1.040	**y2.303**	**y2.292**	**y2.069**
Sergestidae	***	x0.000	x0.002	x0.004	**y0.072**	**y0.100**
Eukrohnia hamata	***	x0.071	y0.403	z0.756	p1.566	**q2.551**
Sagitta gazellae	ns	0.018	0.010	0.041	0.079	0.062
Appendicularia	***	**y32.101**	x11.325	x7.681	x5.463	x4.986

Oithona frigida and *Scolecithricella minor*, and the chaetognath *Eukrohnia hamata* all showed strong depth preference, occurring at significantly higher densities in the 100-150m zone. The copepods *Calanoides acutus*, *Clausocalanus brevipes*, *Eucalanus longiceps*, *Haloptilus oxycephalus*, and sergestid decapods all occurred at significantly higher abundance below 50m. *Calanus simillimus* was an important contributor to zooplankton abundance. It occurred at relatively low densities in the CPR samples but was extremely abundant in the NORPAC samples between 0 and 100m. *Spongiobranchea australis* occurred in samples below 20m while ostracods were most abundant in the 20-50m sample. The euphausiid *Euphausia triacantha* was absent from the CPR samples and was most abundant in the 50-100m sample group. *Primno macropa* was absent from CPR samples but occurred at similar densities in all of the NORPAC samples. *Phalacrophorus pictus*, *Clio pyrimidata*, *Limacina* spp., *Clausocalanus laticeps*, *Ctenocalanus citer*, *Metridia lucens*, *Themisto gaudichaudii*, *Euphausia frigida*, *E. vallentini* and *Sagitta gazellae* all occurred at similar densities in all sample groups.

Figure 3.9 illustrates the latitudinal abundance distribution of the three dominant taxa in the CPR samples: foraminifera, *O. similis* and appendicularians. The abundance levels of all three taxa were highest south of ~ 55°S (and the PF-N), in the Permanently Open Ocean Zone of the Antarctic region. Lowest densities were recorded north of the SAF-S, although this may have been due to high radiation levels (Figure 3.5a). Both foraminifera and *O. similis* had two peaks in abundance, corresponding with periods of low radiation, between the PF-N and PF-S, and south of the PF-S. Appendicularia had a single major density peak in the zone between the two branches of the Polar Front. As would be expected for dominant taxa, their abundance distribution closely followed that of total levels (Figure 3.5a).

Cluster analysis of CPR samples identified two clusters at the ~ 63% level of dissimilarity (Figure 3.10a). Cluster 1 comprised samples south of ~ 51.50°S, while Cluster 2 comprised samples north of this latitude. Correspondence Analysis largely produced the same two sample groupings identified by cluster analysis, and they were subsequently given the same numbers (Figure 3.11a). The two groupings separated CPR samples collected to the south of the SAF-S (Group 1) from those collected between the SAF-S and the SAF-N (Group 2). The SAF-N was not crossed by the CPR during this survey.

The cluster analysis of NORPAC stations identified 3 sample groupings at ~ 84% dissimilarity (Figure 3.10b). Group 1 comprised NORPAC stations 1, 2 and 3

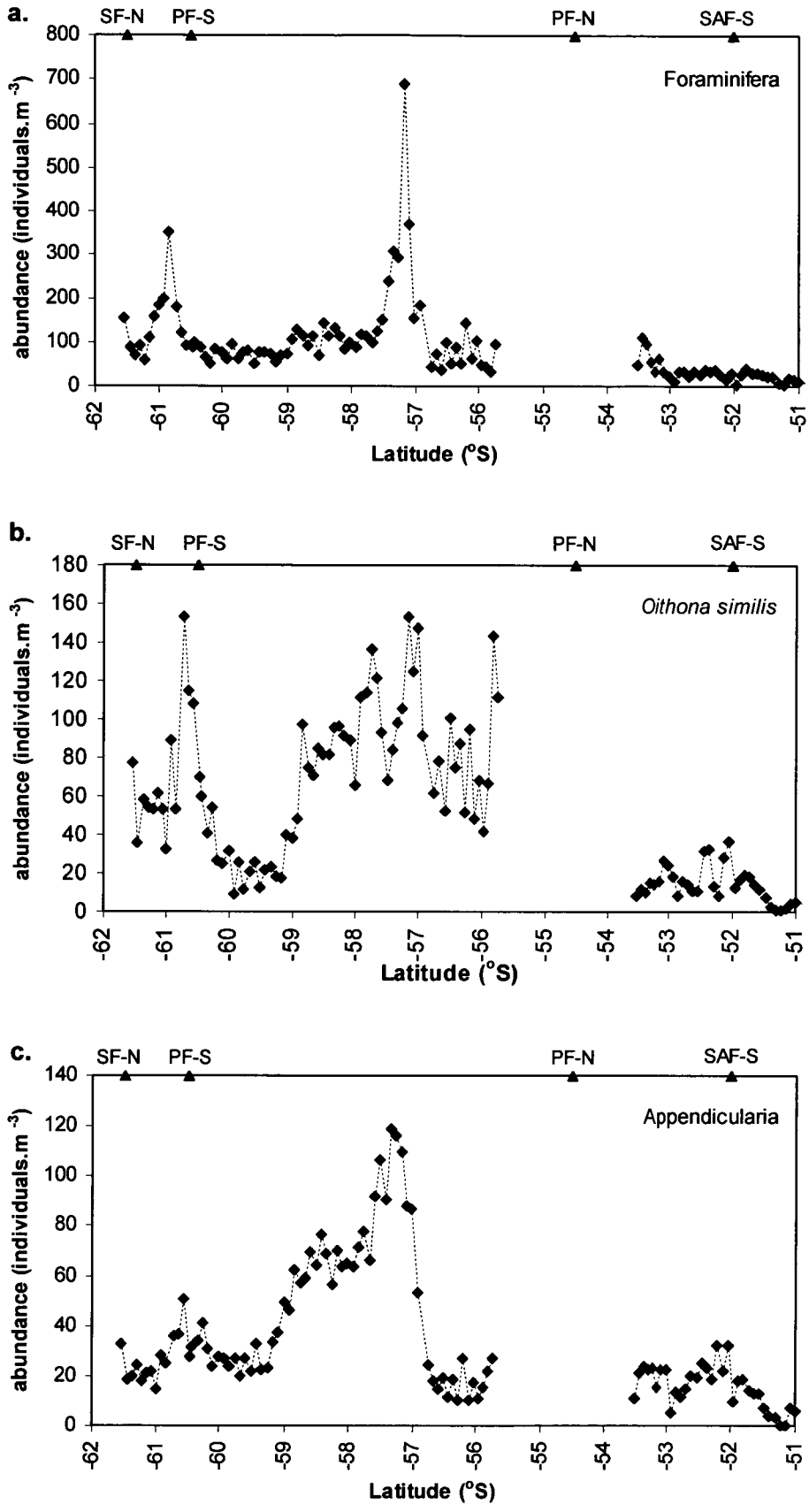


Figure 3.10. Abundance (individuals.m^{-3}) of **a.** foraminifera, **b.** *Oithona similis* and **c.** appendicularians in CPR samples. The location of fronts is indicated by ▲: SF-N – northern Southern Front; PF-S – southern Polar Front; PF-N – northern Polar Front; SAF-S - southern Sub-Antarctic Front.

a.

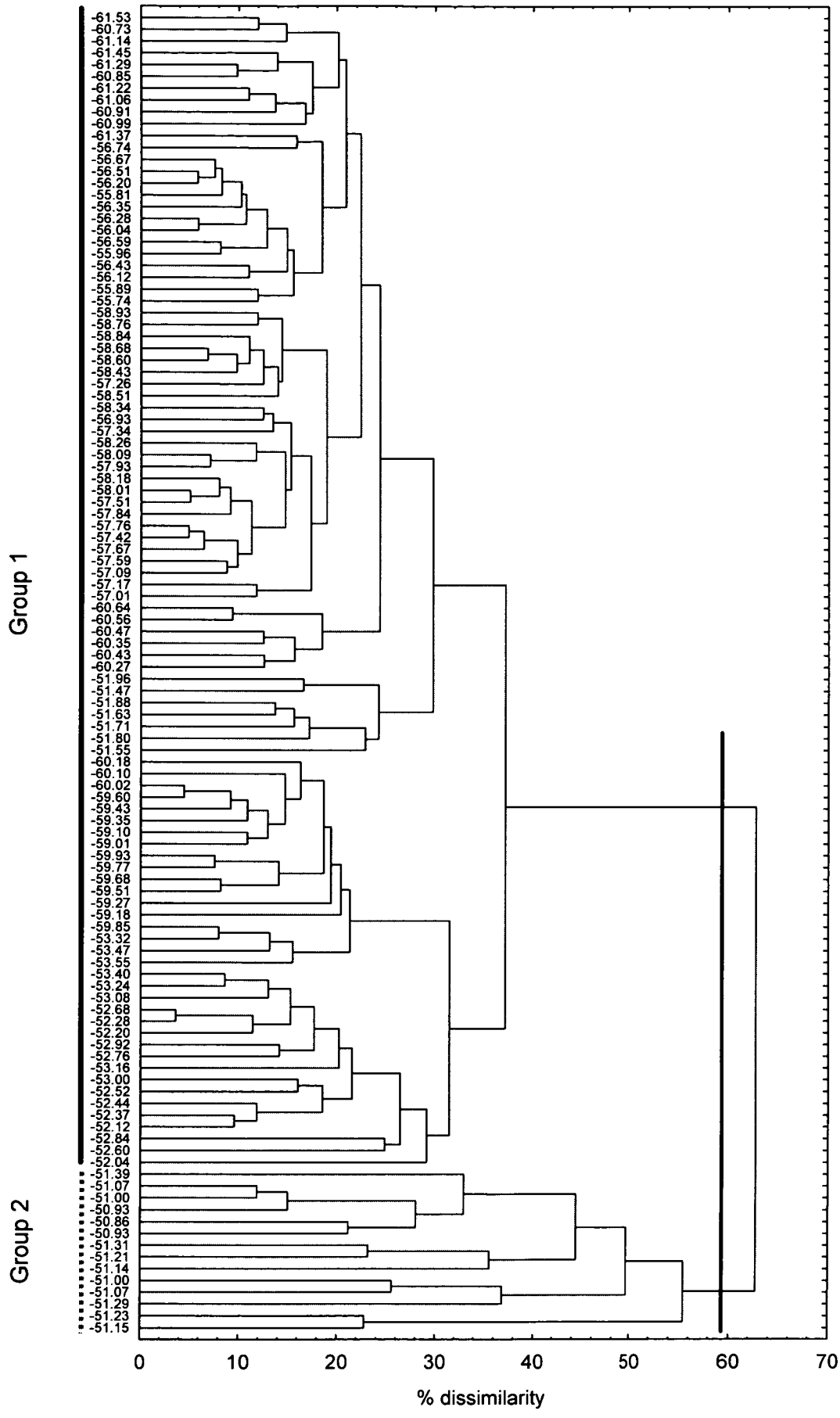


Figure 3.10a. *legend overleaf...*

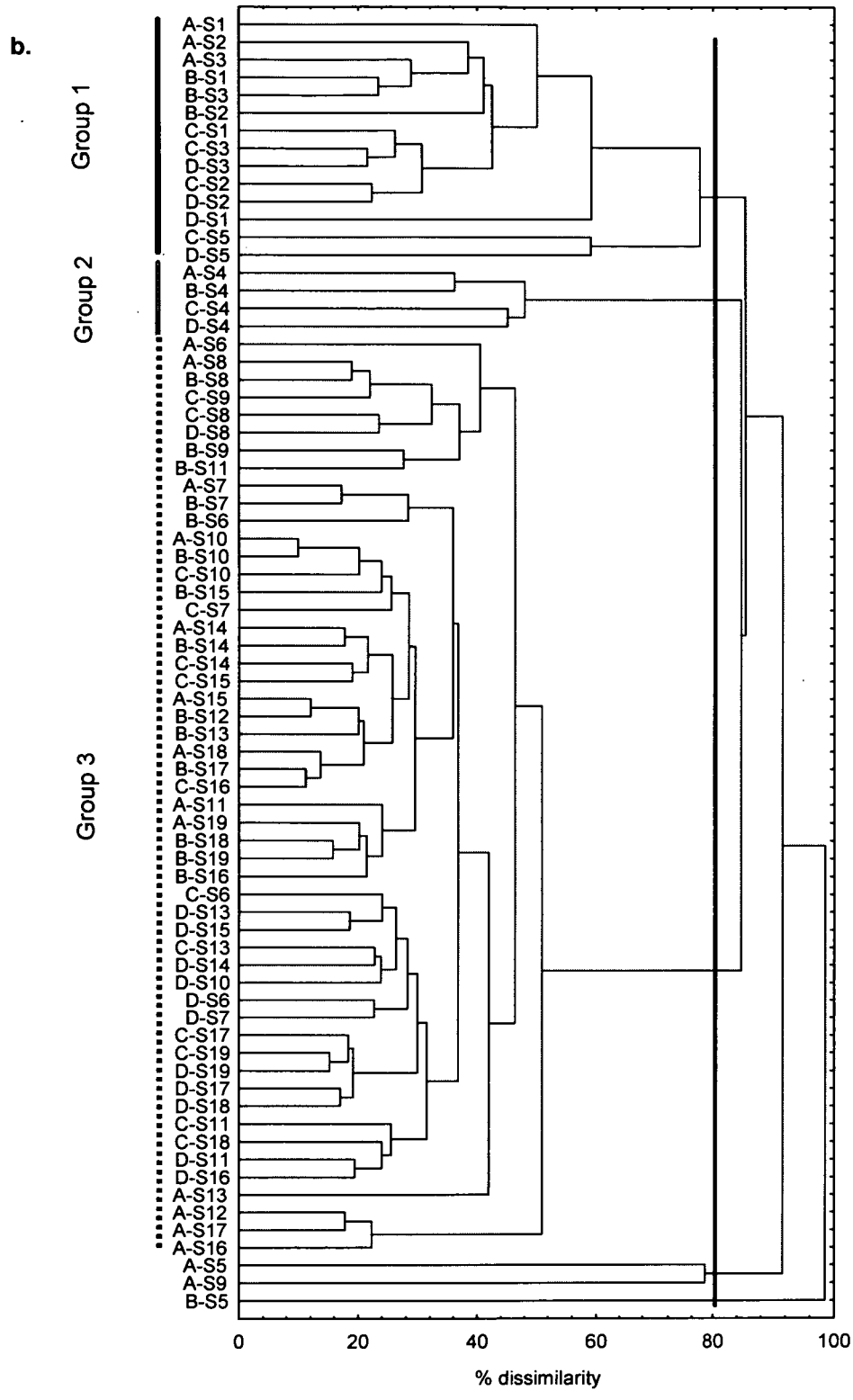


Figure 3.11. Cluster analysis of **a.** CPR samples and **b.** NORPAC net tows using $\log_{10}(x+1)$ transformed species abundance data and the Bray-Curtis dissimilarity index. Clustering was by Un-Weighted Pair-Group Average linkage. CPR samples are labeled by latitude (°S), and NORPAC net tows are labeled by station number (Figure 3.2) and depth zone (A = 0-20m; B = 20-50m; C = 50-100m; D = 100-150m).

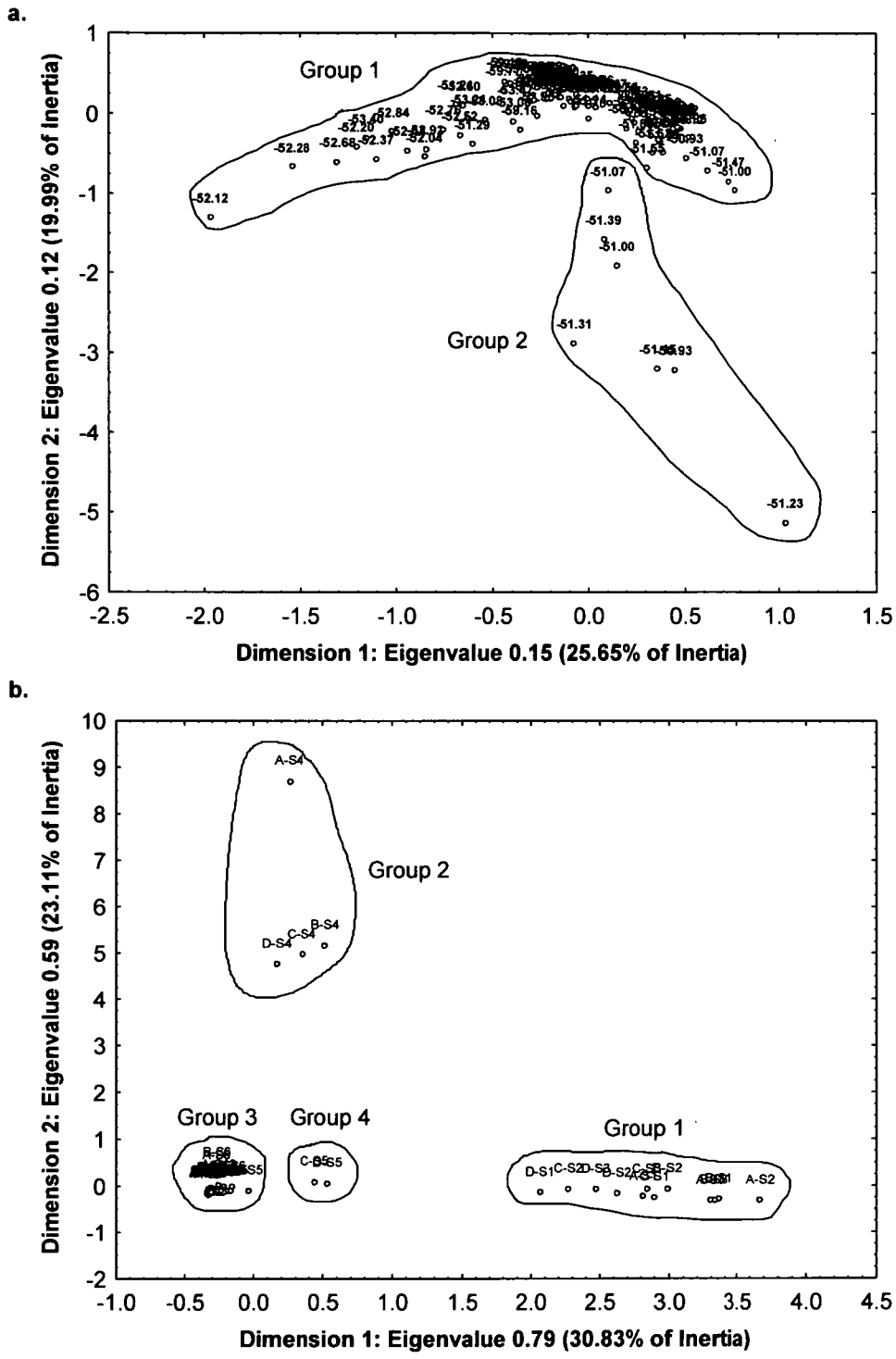


Figure 3.12. Correspondence Analysis of **a.** CPR samples and **b.** NORPAC net tows using un-transformed abundance data for species occurring in > 4% of samples. In **a** CPR samples are labeled by latitude (°S), and in **b** NORPAC net tows are labeled by station number (Figure 3.2) and depth zone (A = 0-20m; B = 20-50m; C = 50-100m; D = 100-150m).

which were located north of the SAF-N, and station C-S5 and D-S5 from just south of the SAF-N. Group 2 comprised the Station 4 samples, located at the SAF-N. Group 3 comprised the remaining stations, all of which were located to the south of the SAF-N. As for the CPR samples, NORPAC cluster groupings were largely replicated by Correspondence Analysis (Figure 3.11b). However, stations C-S5 and D-S5 separated from Group 1 to form Group 4. Indeed, inspection of the cluster dendogram demonstrated that stations C-S5 and D-S5 separated from the remaining Group 1 samples at ~ 75% dissimilarity.

3.4. Discussion

The average CPR towing depth during this survey (~ 10.5m) was somewhat deeper than that of the SAHFOS northern hemisphere survey (6.7m). Sea conditions, visibility, and the presence of icebergs in the Southern Ocean result in periodic reductions in ship speed to 8-10 knots and a corresponding CPR depth of 15-20m. There was therefore some variation in sampling depth during the voyage, but the majority of this variation occurred between 0 and 20m. The 0-20m NORPAC depth zone was therefore a good approximation of CPR depth for a comparison between the two sampling apparatuses.

Reduced day-time zooplankton abundance levels were evident for CPR samples and all NORPAC depth zones, most likely due to diel vertical migration (e.g. Ward et al. 1995). The high temporal resolution and consistent shallow sampling depth of the CPR made it particularly effective at illustrating the cyclical nature of plankton migration, and consequently surface abundance levels. This is fitting given that the CPR was designed to integrate plankton patchiness (Hardy 1936a). A high degree of variation was evident in the abundance levels of NORPAC samples, both within and between stations. The discontinuous nature of vertical net hauls would have contributed to this, coupled with day-night differences in the timing of net hauls.

Large diel variation in diversity and dominance was recorded for the CPR and 0-20m samples. In the 0-20m samples this was principally due to changes in the relative abundance of species, stemming from night-time migration into the surface waters. The CPR values, however, were affected by both changes in relative abundance and increased species richness. Since the CPR and 0-20m NORPAC samples were collected from approximately the same depth zone, it would appear

that the increased diversity and decreased dominance in CPR samples were influenced by a combination of night-time migration and decreased night-time net avoidance success. Clark et al. (2001) suggested that despite the high towing speed of the CPR avoidance may be an important factor given its small entrance aperture and a possible "bow-wave effect" telegraphing its approach.

The poor representation of most zooplankton groups in CPR samples, in comparison to NORPAC nets, was further indication that the two net systems differed in their sampling efficiency. Mechanical damage to plankton may have been a contributing factor to this in CPR samples. The plankton collected by the CPR are sandwiched between two nets, a process which frequently flattens animals. Soft bodied species can be damaged beyond recognition and consequently are not even recorded in higher taxonomic groups. This may account for the low species richness of gelatinous plankton, pteropods, polychaetes and other soft bodied species in the CPR samples. However, hard bodied taxa including euphausiids, amphipods and decapods remain identifiable to at least the level of Order. The low abundance of these hard bodied taxa in CPR samples relative to NORPAC nets therefore supported higher CPR avoidance.

Zooplankton communities were strongly structured in the vertical plane and the distributions of a number of species varied significantly between depth zones. This was reflected by increased species richness and diversity, and decreased dominance, with depth. The shallow sampling depth of the CPR therefore had a significant bearing on the zooplankton collected. The CPR samples were most similar to the 0-20m NORPAC samples, although having lower species richness and diversity, and higher dominance, ostensibly due to under-sampling. However, both the CPR and 0-20m NORPAC samples shared distinct surface community characteristics, including relatively high densities of *O. similis* and appendicularians.

Despite depth related community differences little variation was evident in total abundance levels between the depth zones sampled by the NORPAC nets. Although under-sampling components of the community, average zooplankton densities were higher in the CPR than NORPAC samples. This finding was in stark contrast to Clarke et al.'s (2001) comparison of WP2 vertical nets and the CPR survey in the North Sea which found abundance levels in the WP2 survey to be an order of magnitude higher than the CPR survey. However, there were fundamental differences in methodology between these two surveys, including mesh size (200μm

in the WP2 survey and 270μm in the CPR survey), depth zones sampled, and the spatial scale of sampling.

The relatively high CPR abundance in December 2001 was principally due to foraminifera, *O. similis* and appendicularians. A minimum of 15 days separated the southern (NORPAC) and northern (CPR) transects and the increase in densities during this period may have been influenced by the advection of waters with high zooplankton densities into the study area. However, the majority of the high density samples recorded on the CPR transect occurred in the low current velocity inter-frontal region between the PF-N and PF-S which would have been least affected by advective processes (Sokolov and Rintoul 2002). Furthermore, Hosie et al. (2003) demonstrated a high degree of similarity in zooplankton densities between three simultaneous transects completed along 25°E, 110°E and 160°E, pointing to factors other than advection as being responsible for the density increase observed during the present study. The minimum of 15 days between transects may have been of long enough duration for growth of appendicularians and *O. similis* sufficient to increase their catchability by the 270μm mesh. *Oithona similis* copepodites have a mean stage duration of 14 to 30 days (Fransz and Gonzalez 1995; Atkinson 1998), while appendicularian growth rates are extremely high, although being strongly related to temperature (Deibel 1998, Hopcroft et al. 1998, Sato et al. 2001). Generation times of 6 days have been measured at temperatures of 13-15°C, decreasing to 3 days at 25°C. The growth rates of these taxa are therefore sufficient to account for the increase in abundance observed in the surface waters between the southern and northern transects of this study. Population growth and development may also have been responsible for the high densities of *Rhincalanus gigas* nauplii recorded in the CPR samples. *Rhincalanus gigas* C1 copepodites have been recorded as having a 10 day duration at sea surface temperatures of ~ 3°C in the vicinity of South Georgia island (Shreeve and Ward 1998). The high abundance of *R. gigas* nauplii is consistent with the peak in nauplii observed in late November in the Scotia Sea (Atkinson 1991).

Voronina (1972) demonstrated that the seasonal development of zooplankton populations in the Southern Ocean commences first in the north, while lagging in the south. Accordingly, one would expect an increase in average population size to be first evident in the Polar Frontal Zone (PFZ), between the PF-N and SAF-S, rather than in the region south of the PF-N. The higher densities of foraminifera, *O. similis* and appendicularians south of the PF-N therefore points to strong latitudinal

differences in zooplankton populations. It is possible that an additional factor influenced the densities of the smaller components of the zooplankton recorded in this study, e.g. *O. similis*. The 270μm mesh has been calculated to collect only 3.24% to 3.8% of adult *Oithona* spp. (Robertson 1968, Gallienne and Robins 2001). Given that a mesh size approximately 75% of copepod width is required to catch 95% of all individuals of a given size (Nichols and Thompson 1991), the densities recorded by the CPR survey certainly under-represent the smaller size fractions of copepod populations and communities (e.g. *Oithona* spp., C1-C3 copepodites of *Ctenocalanus* spp. and *Clausocalanus* spp.). A feature of the CPR samples collected between the PF-N and the SF-N was the occurrence of large diatoms on the nets. It is possible that the presence of diatoms reduced the size of the CPR mesh, enabling it to more effectively sample *O. similis* at a time in the season when the population is dominated by early copepodite stages, as well as other small components of the zooplankton (Dubischar et al. 2002).

The oceanographic data clearly illustrated the physical zonation of the Southern Ocean. The strongest physical gradients occurred at the northern and southern branches of the SAF. Both of these fronts were associated with a 3°C horizontal change in temperature over approximately 0.5° latitude, and a marked salinity change occurred at the SAF-N. To the south of the SAF-S physical gradients were generally low with a horizontal steepening in the vicinity of the PF-S and SF-N, although not as severe as that associated with the SAF. Within the region where zooplankton were collected the SAF represented an important biogeographic boundary. Despite the sampling differences between the CPR and NORPAC nets, both apparatus' demonstrated that the communities to the north of the SAF-S were distinct from those to the south. The lack of horizontal community variation between the PF-N and PF-S reflected the comparative homogeneity of the physical environment in this region.

Unfortunately the samples from this study did not allow a thorough comparison of communities to the north and south of SAF-N. The CPR run did not extend to the north of the SAF-N, and only one NORPAC station (S5) was conducted between the northern and southern branches of the SAF. The two S5 samples below 50m grouped out with stations to the north of the SAF-N, while the two above 50m grouped separately. It was therefore not clear whether the region between the two branches of the SAF had distinct community characteristics or not. However, importantly, this study demonstrated that, despite under-sampling some

components of the zooplankton community, the CPR provided sufficient taxonomic resolution to identify the biogeographic boundary represented by the SAF.

Although, the primary focus of this study was the identification of the sampling characteristics of the Type II Mark V CPR, the important additional function was performed of providing a means for direct comparison of CPR and vertical net data. The study highlighted many sampling differences between the two net systems, however, a number of taxa showed no significant difference in densities between the two net types. This indicated that, at least in early summer, they were effectively sampled by both nets and were not distributed unequally amongst depth zones. These taxa therefore provide a means for comparison between surveys (past and future) conducted using traditional nets and CPRs, potentially giving insights into long-term temporal variability in the Southern Ocean.

3.5. Summary

The average sampling depth of the CPR was shown to be ~ 10.5m. This shallow sampling depth had a significant influence on the zooplankton communities sampled by this apparatus. Depth integrated NORPAC net samples demonstrated fine-scale depth related variation in zooplankton communities in the upper 150m of the water column. Although there was little variation in abundance between depth zones, both species richness and diversity increased with depth while dominance decreased. The communities sampled by the CPR were characterised by low species richness and diversity, and high dominance, even in comparison to NORPAC net samples collected from an equivalent depth zone (0-20m). These differences could be attributed to sampling differences between the two net systems. Fast moving and delicate components of the plankton community were poorly represented in CPR samples due to day-time avoidance and mechanical damage to specimens respectively. Despite sampling differences between the CPR and NORPAC nets, similarities were identified in the surface community, including high densities of *Oithona similis* and appendicularia. Furthermore, the multivariate analysis demonstrated that the CPR accurately identified latitudinal variation in community structure, in this instance the biogeographic boundary represented by the SAF-S.

Chapter 4

Zonal Structure of zooplankton communities in the Southern Ocean south of Australia: results from an 1171 nautical mile CPR transect

4.1. Introduction

The Southern Ocean is a strongly zonal environment. Oceanographically it is divided into two major current systems, the eastward flowing Antarctic Circumpolar Current (ACC) and the westward flowing Coastal Current (CC) (Foster 1984), both of which are sub-divided by numerous, generally circumpolar frontal systems (Lutjeharms and Vallentine 1984, Nowlin and Klinck 1986, Orsi et al. 1995, Belkin and Gordon 1996). These fronts are regions of steep physical gradients, separating zones of relatively uniform water mass properties, and they are recognized as important biogeographic boundaries for zooplankton (Deacon 1982). Studies in the Atlantic and Indian Ocean sectors of the Southern Ocean have variously identified the Sub-Tropical Front (STF), Sub-Antarctic Front (SAF), Polar Front (PF) and Antarctic Divergence (AD) as separating distinct communities (Tarling et al. 1995, Pakhomov and McQuaid 1996, Errhif et al. 1997, Gibbons 1997, Atkinson and Sinclair 2000). South of the PF the zonal distribution of zooplankton is further influenced by the interaction of frontal structure with the seasonal sea-ice (Hopkins et al. 1993, Hosie 1994, Chiba et al. 2001).

Although circumpolar in nature, Southern Ocean fronts demonstrate considerable spatial variation in location, proximity to adjacent fronts, volume transport, and associated mesoscale features, including eddies and meanders (Emery 1977, Gordon et al. 1978, Gamberoni et al. 1982, Bryden 1983, Belkin and Gordon 1996, Orsi et al. 1995). Similarly, there is substantial circumpolar variation in the extent of the sea-ice zone and its seasonal dynamics (Worby et al. 1998, Constable et al. 2003). Such physical variation has important implications for zooplankton. Community structure is significantly influenced by both regionally specific oceanographic structure, e.g. Weddell-Scotia Confluence (Deacon 1982, Marin 1987, Hopkins et al. 1993) and topographic forcing at the Kerguelen Plateau (Errhif et al. 1997), and sea-ice dynamics (Loeb et al. 1997, Nicol et al. 2000a). Recently, an intensive oceanographic study south of Australia has demonstrated the occurrence of multiple branches of the SAF, PF and Southern Front (SF) in this

sector (Sokolov and Rintoul 2002). All of these frontal branches were deep reaching features and regions of enhanced volume transport. To date, no study has investigated the implications of this complex oceanographic structure for zooplankton communities. The Australian sector is further characterised by substantial longitudinal variation in sea-ice extent, with the Seasonal Ice Zone (SIZ) being narrow between 115°E and 150°E (equivalent to the extent of the marginal ice zone in other areas of Antarctica) and widening west of 115°E (Worby et al. 1998).

The vast majority of zooplankton sampling in the Southern Ocean has been conducted using vertically / obliquely hauled nets. However, these net systems are not ideal for assessing the relationship between fine-scale zonal variation in the physical environment and zooplankton communities over large areas. Observations from past Southern Ocean studies show that the time constraints associated with vertical / oblique net tows typically limit sampling resolution to > 30nm between hauls and require surveys of > 30 days duration (e.g. Hopkins 1985a, Boysen-Ennen et al. 1991, Yamada et al. 1992, Fransz and Gonzalez 1995, Siegel and Harm 1996, Pakhomov et al. 1997, Voronina 1998, Takahashi et al. 1998, Duro et al. 1999, Pakhomov et al. 2000). The coarse spatial resolution of samples is likely to be strongly affected by small scale zooplankton patchiness, while the duration of surveys (> 30 days) may be sufficient for intra-survey changes in population and community structure to have occurred (e.g. Hopkins et al. 1993, Errhif et al. 1997, Fransz and Gonzalez 1997). Recently, Optical Plankton Counters (OPCs) have demonstrated variation in the distribution of zooplankton densities and size fractions on the scale of ~ 5nm (Labat et al. 2002, Read et al. 2002, Pollard et al. 2002). However, OPCs can not be reliably used to distinguish species of similar shape (e.g. copepods) (Labat et al. 2002), and therefore have limited value for determining water mass specific zooplankton community structure.

The Continuous Plankton Recorder (CPR) has excellent attributes for examining zooplankton distributions. Operation at high speed (10 to 18 knots), enables continuous 5 nm resolution samples to be collected efficiently and rapidly over large areas (Reid et al. 2003). Despite under-sampling certain components of the zooplankton community, Chapter 3 demonstrated that the CPR is sensitive to frontal boundaries. Following this calibration study a comprehensive CPR transect was completed along the 140°E meridian, spanning all of the major fronts south of the STF. Through detailed multivariate analysis of these high resolution samples Chapter 4 aimed to:

1. define the relationship between the physical environment and zooplankton communities south of Australia in the context of current knowledge of the region's physical oceanography and zonation.
2. provide baseline data on the spatial distribution of zooplankton communities in this region, against which future variation in the zooplankton communities can be measured.

4.2. Methods

4.2.1 Data Collection

Data for this study were collected during the 44th Japanese Antarctic Research Expedition, aboard the RV *Tangaroa*. Between 25 February and 3 March 2002 three CPR tows were completed along the 140°E meridian. An average sampling depth of ~ 10.5m was recorded for the Type II, Mark V CPR in tests from the RV *Aurora Australis* (Chapter 3; Hunt and Hosie 2003), and based on the low inter-vessel depth variation recorded by Hays and Warner (1993), the sampling depth from the RV *Tangaroa* would have been within a few meters of this. Together, the three tows formed an unbroken 1171nm transect between 66.36°S and 47.02°S (Figure 4.1). The collection, treatment and processing of zooplankton samples followed the protocol in Section 2.3.2

The entire contents of each sample was identified and enumerated under a stereo dissecting microscope. Identification of zooplankton was to species and stage level wherever possible, and followed the protocol in Section 2.3.3. All *Euphausia superba* specimens were larval stages (Calyptopis I to Furcilia I). *Thysanoessa macrura* and *Thysanoessa vicina* have overlapping ranges and are morphologically very similar, the only reliable difference being in the petasma of the males (Kirkwood 1982). Consequently these two species were merged as *Thysanoessa macrura / vicina*. Copepodite stages C1 to C3 of *Calanus propinquus*, *Calanus simillimus* and *Calanoides acutus* were not identified to species in all cases, and consequently were merged as large calanoid copepodites (C1-3). Zooplankton abundance was converted to individuals.m^{-3}. No flowmeter was attached to the CPR and filtration efficiency was assumed to be 100%.

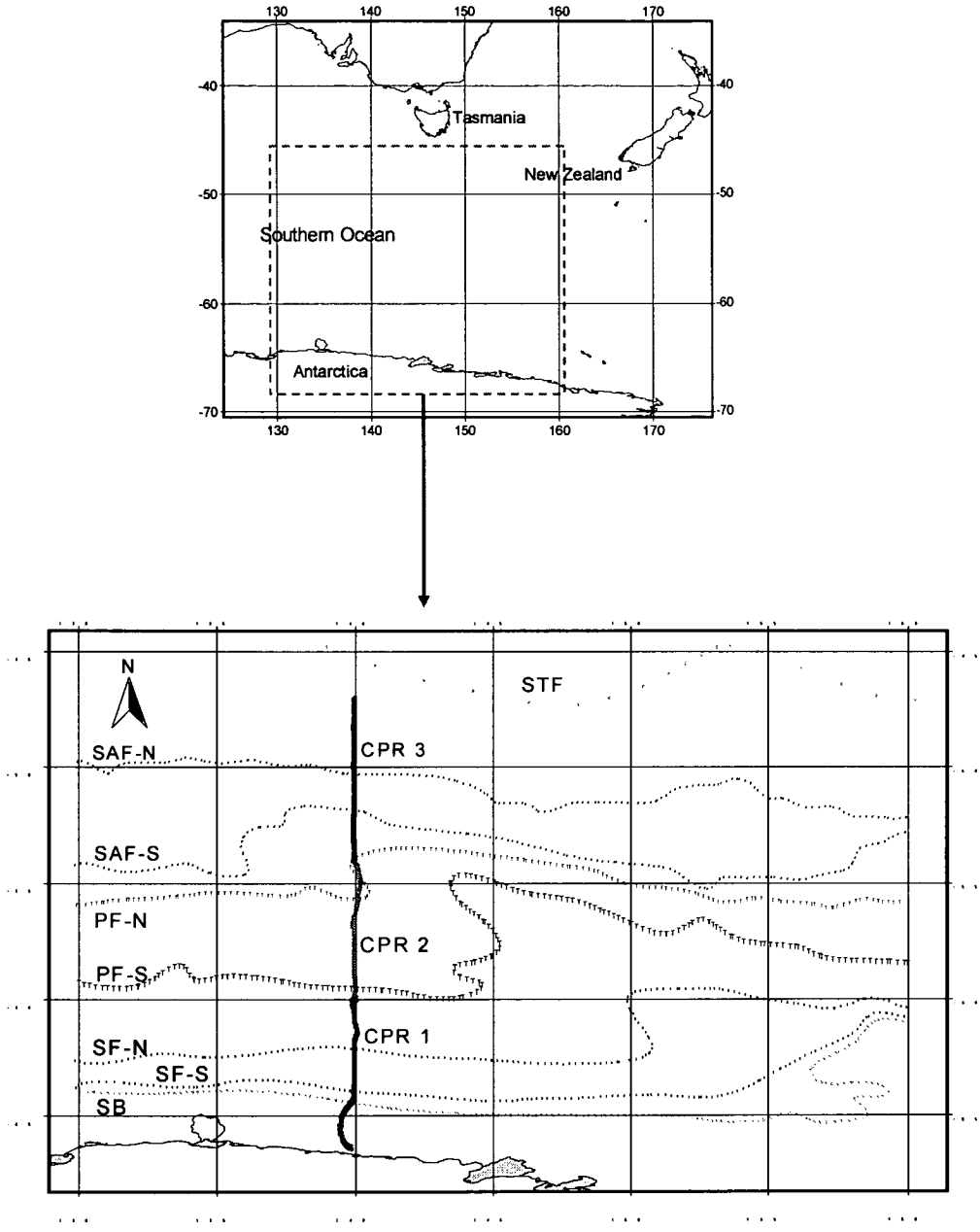


Figure 4.1. The Southern Ocean and its frontal structure south of Australia. The locations of fronts are the average positions given by Sokolov and Rintoul (2002).The location of the three Continuous Plankton Recorder (CPR) transects conducted during this study are indicated. SB – Southern Boundary; SF-S and SF-N (Southern Front – South and North); PF-S and PF-N (Polar Front – South and North); SAF-S and SAF- N (Sub-Antarctic Front – South and North).

Underway Sea Surface Temperature (SST), Surface Salinity (SS), Photosynthetically Active Radiation (PAR) and fluorometry were measured continuously at one minute intervals along the length of the CPR transect using an Aquapack (Chelsea Instruments, LTD). The salinometer failed south of 59.92°S during CPR sampling. Consequently SS measurements recorded by the RV *Tangaroa* along 140°E from 11 to 12 February (13 days prior to the commencement of the CPR tows), for the region south of 61.12°S, were spliced to the SS data set. Fluorescence readings were converted to chlorophyll *a* biomass using the formula:

$$y = 1.1364x + 0.0503$$

where x is the fluorescence value and y is chlorophyll *a* ($mg.m^{-3}$) (Lorenzen 1966). Alpine and Cloern (1985) demonstrated a linear relationship between *in vivo* fluorescence and chlorophyll *a* within three different phytoplankton size classes, netplankton (> 22μm), nanoplankton (22-5μm) and ultraplankton (< 5μm), but that fluorescence per unit chlorophyll *a* had a significant negative relationship with phytoplankton size. It is therefore possible that chlorophyll a biomass along the transect was influenced by phytoplankton community composition.

In addition to the surface data, nine casts of a SBE 119 CTD system were completed south of 61°S along 140°E (Figure 4.3), between 10 and 12 February. The CTD data was used to produce vertical profiles of temperature and salinity for the upper 1000m of the water column. The positions of fronts along 140°E were determined using the combination of underway and CTD data, in comparison with the definitions and average positions given by Sokolov and Rintoul (2002).

4.2.2. Data Analysis

Species richness / number (*r*) and the Shannon-Weaver diversity index (*H'*) were calculated for each sample. Taxa identified to the genus level were included in these calculations.

$$H' = \sum_{i=1}^{S} p_i . \log_2 p_i$$

Where S is the total number of species and p_i is the proportion of the number of individuals of species i to the total number of individuals.

A sample by taxon matrix was produced for multivariate analysis of community structure. Copepodite stages C1 to C3 and unidentified nauplii were excluded, while the stages of other taxa were merged. As Southern ocean CPR samples are strongly influenced by diel variation (Hunt and Hosie 2003; Figure 3.5 and 3.6), the data set was divided into night (135 samples) and day (105 samples), determined by the level of PAR. Night was defined as PAR < 100 $\mu mol.s^{-1}.m^{-2}$. The night and day matrices were subsequently interrogated independently using a combination of Cluster Analysis and Correspondence Analysis.

Cluster analysis was carried out on the full data set (48 taxa) and followed the protocol described in Section 3.2.2.2. After $\log_{10}(x+1)$ transformation of abundance levels, clustering was performed using the Bray-Curtis dissimilarity coefficient and Un-Weighted Pair Group Average linkage (Field et al. 1982). Dufrene and Legendre's (1997) Indicator Values (IndVal) were calculated at each level of cluster separation, providing insight into the cause of cluster separation, and the centre of distribution of species. The IndVal method combines measures of group specificity (A_{ij}) and group fidelity (B_{ij}) and is thus complementary to the Bray-Curtis dissimilarity coefficient.

$$A_{ij} = \text{Nindividuals}_{ij} / \text{Nindividuals}_{i}$$

and

$$B_{ij} = \text{Nsamples}_{ij} / \text{Nsamples}_{j}$$

Nindividuals_{ij} is the mean number of individuals of species i in the samples of cluster j, while Nindividuals_{i} is the sum of the mean numbers of individuals of species i over all clusters. Nsamples_{ij} is the number of samples in cluster j where species i is present, while Nsamples_{j} is the number of samples in cluster j. Subsequently the indicator value was calculated as:

$$\text{IndVal} = A_{ij} \times B_{ij} \times 100$$

The values of A and B were multiplied as they represented independent information about species distribution, and further multiplied by 100 to produce percentages. Indicator values of ≥ 25 % were used, which meant that a taxon was present in ≥

50% of samples in a cluster and that its relative abundance in that cluster was ≥ 50%. One-way ANOVA was used to test the hypothesis that species abundance levels, total abundance, diversity indices and environmental variables did not differ between the sample clusters. Where significant differences were detected Newman-Keuls multiple range tests were run to identify inter-cluster differences.

Ordination was by Correspondence Analysis as described in Section 3.2.2.2. The analysis was performed on untransformed data comprising taxa occurring in > 4 % of samples. Regression analysis was used to investigate the relationship between the first two dimensions of the resulting ordination and SST, SS and chlorophyll *a*. Second order polynomial regression provided the best fit.

4.3. Results

4.3.1 Oceanography and Physical Zonation

Both SST and SS values varied substantially along the length of the transect (Figure 4.2a,b) and overall there was good correspondence between regions of steep physical change and the average positions of fronts identified by Sokolov and Rintoul (2002). The steepest gradient of change in both SST and SS was associated with the northern branch of the Sub-Antarctic Front (SAF-N), located at approximately 50.38°S.

A weaker gradient at ~ 52°S marked the position of the SAF-S. The SAF-N is the southern extent of the Sub-Antarctic Zone (SAZ), bounded in the north by the Sub-Tropical Front. The region between the two branches of the SAF has been called the Inter Sub-Antarctic Front Zone (ISAZ). A drop in SST at 56.27°S and 59.17°S indicated the northern and southern branches of the Polar Front (PF) respectively. There was little variation in SS between the SAF-S and the PF-S (average = 33.75). Here the region between the SAF-S and the PF-N is referred to as the Polar Frontal Zone (PFZ), and the region between the two branches of the PF as the Inter Polar Frontal Zone (IPFZ) (following Trull et al. 2001b).

In the vertical profiles the SF-N was defined by the southern most extent of water warmer than 2°C (Sokolov and Rintoul 2002), placing it at ~ 62.25°S (Figure 4.3). In the surface profiles the SF-N was associated with a drop in both SST and SS. The SF-S was defined by salinity > 34.73 along S_{max} at 800m (Table 2.1), placing it at ~ 64.30°S. To the south of the SF-S was the Southern Boundary (SB) of

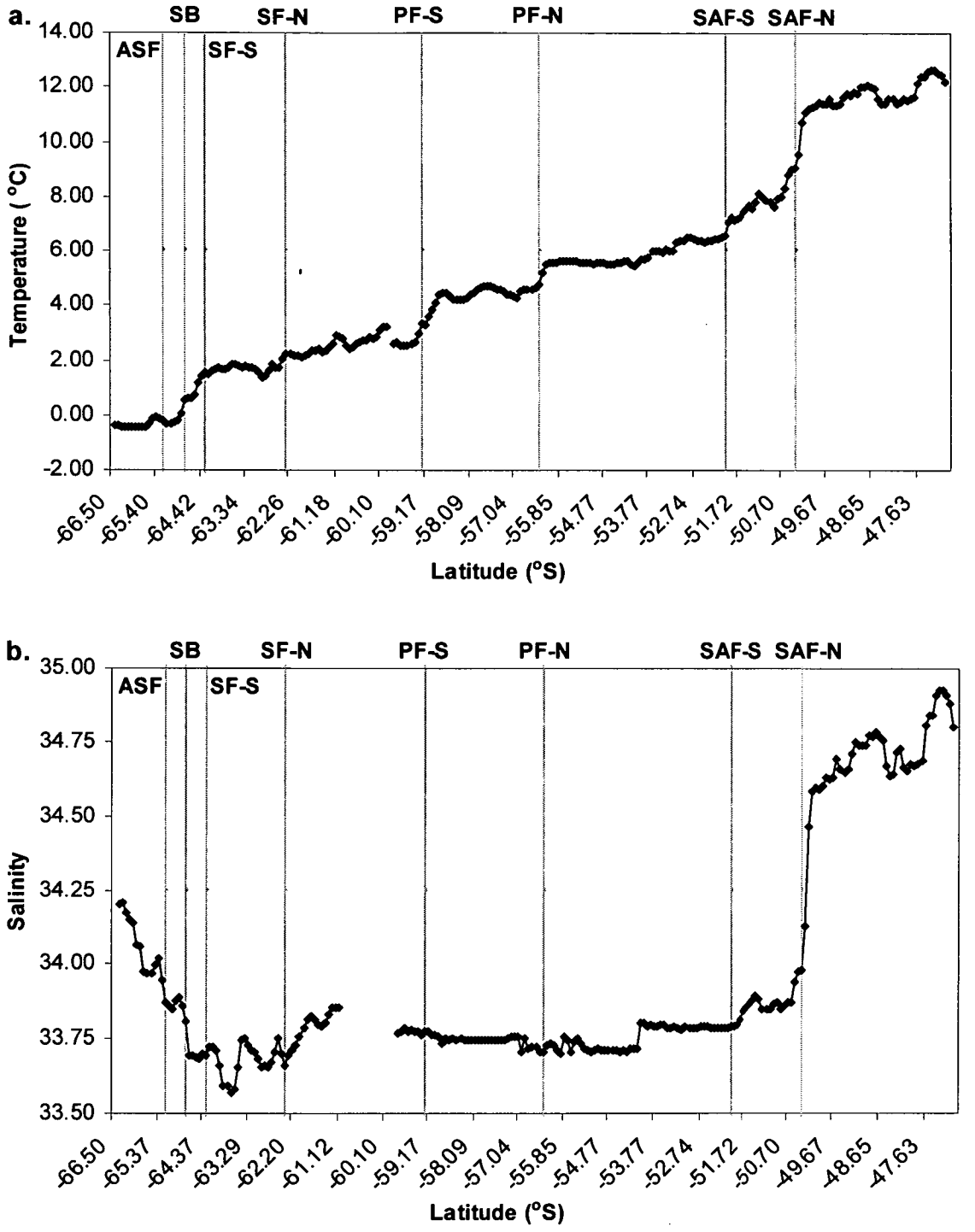


Figure 4.2. a. Sea Surface Temperature (°C) and **b.** Surface Salinity recorded along the 140°E transect from 25 February to 3 March. The salinity data south of 61.12 S were collected between 11 and 12 February, 13 days prior to the CPR transect. Frontal positions are indicated for the ASF – Antarctic Slope Front; SB – Southern Boundary; SF-S and SF-N (Southern Front – South and North); PF-S and PF-N (Polar Front – South and North); SAF-S and SAF-N (Sub-Antarctic Front – South and North).

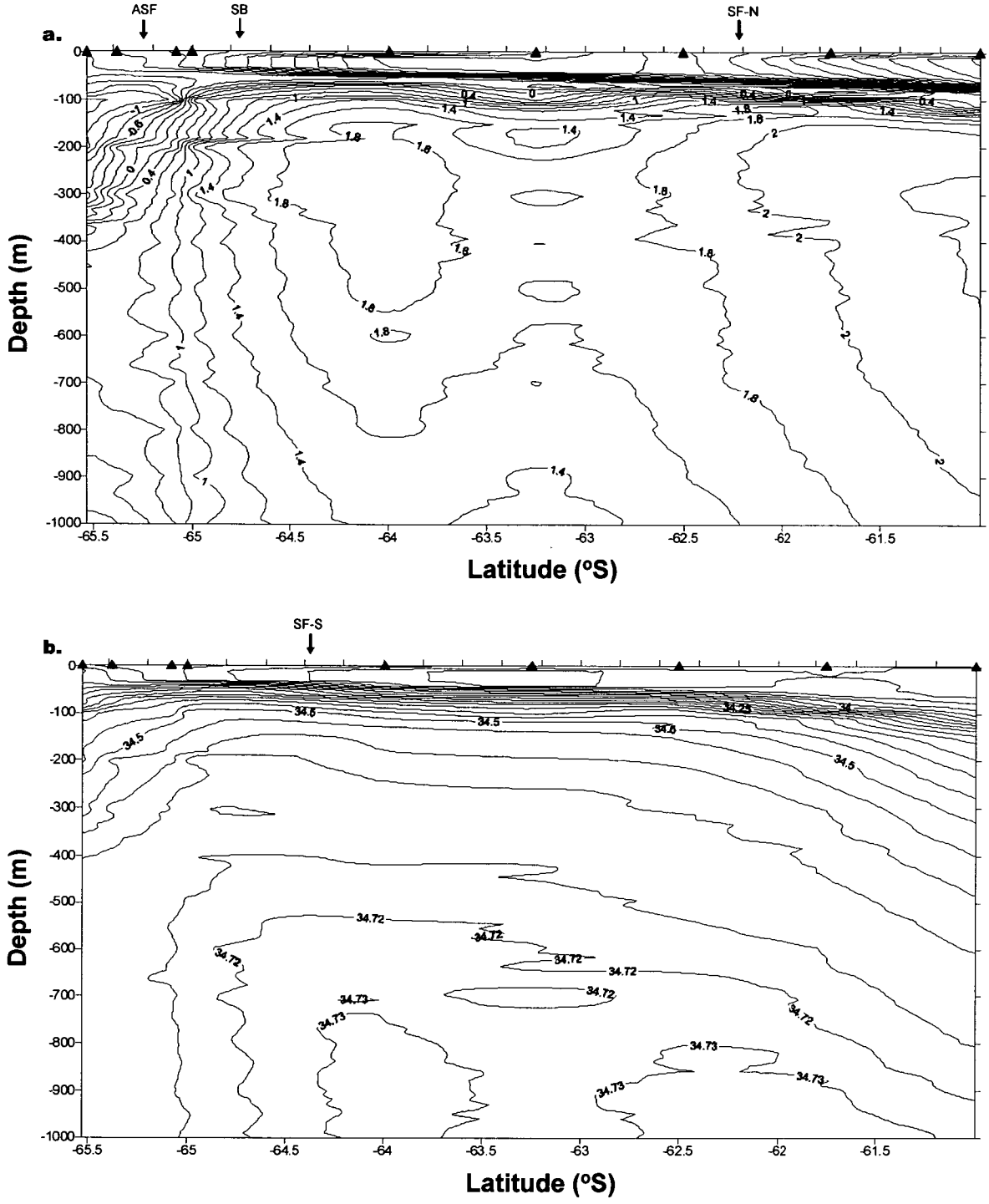


Figure 4.3. Vertical profiles of **a.** temperature (°C) and **b.** salinity for the upper 1000m of the water column between 61.00°S and 66.50°S. The locations of the northern and southern branches of the Southern Front (SF-N and SF-S), the Southern Boundary (SB) and the Antarctic Slope Front (ASF) are indicated. The locations of CTD stations are indicated by ▲.

Table 4.1. Oceanographic Zones in the Australian sector of the Southern Ocean south of the Sub-Tropical Front.

Zone	Abbreviation	Location	
Sub-Antarctic Zone	**SAZ**	Sub-Tropical Front to the northern branch of the Sub-Antarctic Front	
Inter Sub-Antarctic Front Zone	**ISAFZ**	Between the northern and southern branches of the Sub-Antarctic Front	
Polar Frontal Zone	**PFZ**	Southern branch of the Sub-Antarctic Front to the northern branch of the Polar Front	Permanently Open Ocean Zone (POOZ)
Inter Polar Frontal Zone	**IPFZ**	Between the northern and southern branches of the Polar Front	
Northern Antarctic Zone	**AZ-N**	Between the southern branch of the Polar Front and the northern branch of the Southern Front	
Southern Antarctic Zone	**AZ-S**	Northern branch of the Southern Front to the Southern Boundary of the Antarctic Circumpolar Current	Seasonal Ice Zone (SIZ)
South of the Southern Boundary	**S of SB**		

the ACC, defined by the southern limit of θ_{max} water warmer than 1.5°C (Table 2.1). Using this feature the SB was located at ~ 64.80°S (Figure 4.3). In the surface data the SB was associated with a rapid southward decrease in SST and increase in SS. The close proximity of the SF-S and the SB observed during this study is a characteristic feature along 140°E, and previous sections along this transect line have even shown these two fronts to be merged (Sokolov and Rintoul 2002). This study therefore focused on the SB which had the strongest surface expression. The region between the PF-S and SF-N was called the northern Antarctic Zone (AZ-N), and the region between the SF-N and the SB the southern Antarctic Zone (AZ-S).

Along 140°E the SF-N marks the average position (~ 62.5°S) of the maximum winter sea-ice extent (Worby et al. 1998). The region south of and including the AZ-S therefore constitutes the Seasonal Ice Zone (SIZ), although the sea-ice had receded south of the survey area by the end of December 2001 (Hirawake et al. 2003), while the region between the SF-N and the PF-N constitutes the Permanently Open Ocean Zone (POOZ) (Treguer and Jacques 1992). The final front south of the SB was the Antarctic Slope Front (ASF), characterised by the deepening towards the south of isotherms and isohalines, and located at ~ 65.25°S (Figure 4.3). The continental slope and shelf proper commenced south of ~ 65.50°S. A summary of the zonal structure along 140°E is presented in Table 4.1.

4.3.3. Chlorophyll *a* and Zooplankton densities

Fluorescence values demonstrated a diel cycle due to daylight quenching, and this was evident in the chlorophyll *a* calculations (Figure 4.4a). Chlorophyll *a* biomass was relatively consistent between 47°S and the PF-S, night time levels averaging 0.42 $mg.m^{-3}$ and day time levels averaging 0.32 $mg.m^{-3}$. Slightly higher levels were evident in the ISAFZ, and to the north of the PF-N. Between the PF-S and SF-N chlorophyll *a* levels were low, averaging 0.20 $mg.m^{-3}$ (night) and 0.15 $mg.m^{-3}$ (day). South of 63°S average chlorophyll *a* levels increased rapidly to 0.61 $mg.m^{-3}$ (night) and 0.41 $mg.m^{-3}$ (day). The SIZ CPR samples were characterised by a high occurrence of diatoms, principally *Thalassiothrix antarctica* and *Nitzschia kerguelensis* (K. Westwood, personal communication). In view of the negative relationship between fluorescence / chlorophyll *a* biomass and phytoplankton size, chlorophyll *a* biomass values for the SIZ were in all probability underestimates (Alpine and Cloern 1985).

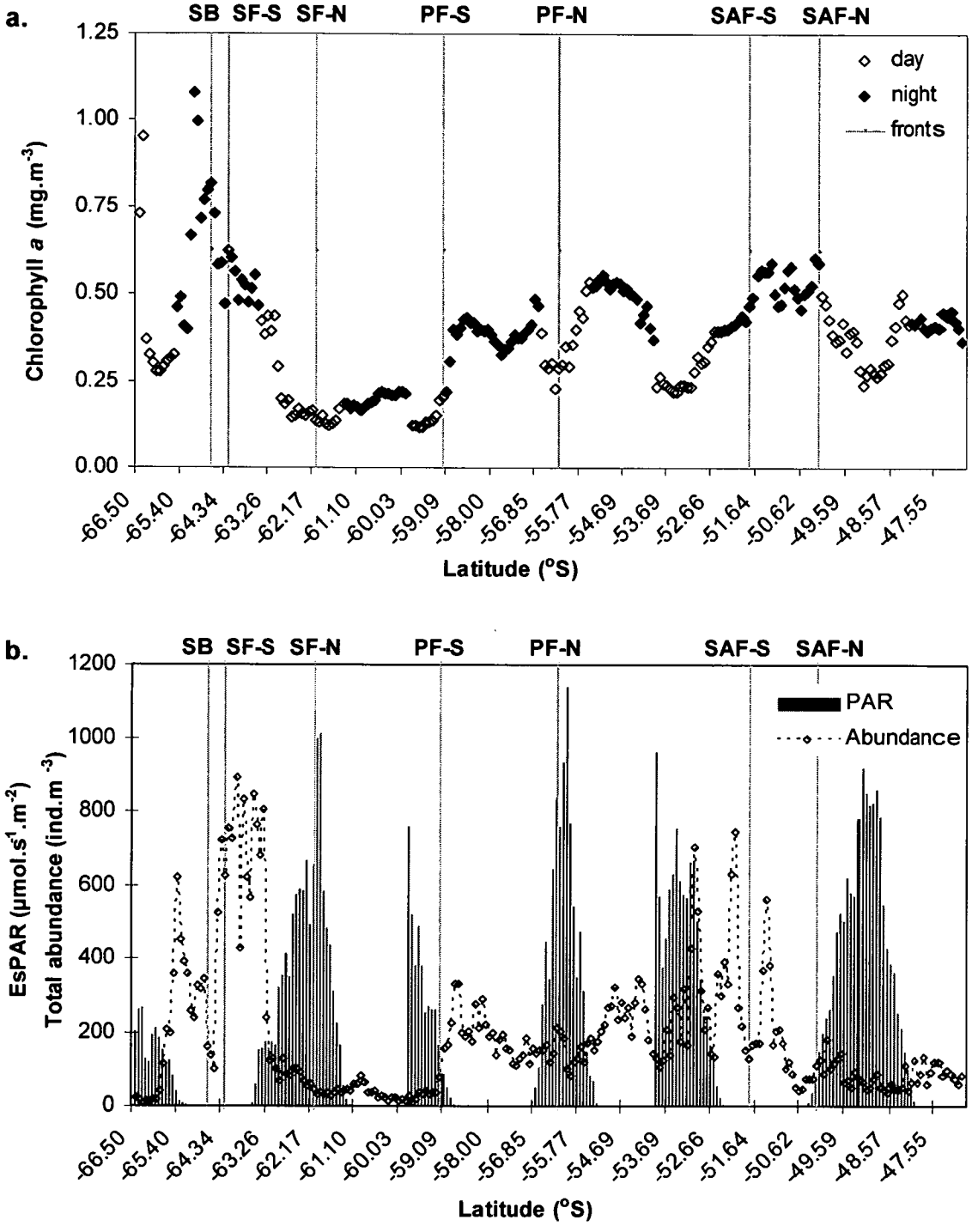


Figure 4.4. a. Chlorophyll *a* biomass determined from fluorescence readings and **b.** average zooplankton abundance (individuals.m^{-3}) plotted in conjunction with Photosynthetically Active Radiation (µmol.s^{-1}.m^{-2}), recorded along 140°E from 25 February to 3 March 2002. In Figure 4.4.a sample points have been coded as day ◊ and night ♦ (Night < 100 mol. s^{-1}.m^{-2}). Frontal positions are indicated and follow those in Figure 4.2.

Zooplankton densities were highly variable, but demonstrated an inverse relationship with PAR (Figure 4.4b). Levels were low in the SAZ (average = 81.30 ind.m^{-3}), increased in the ISAFZ, and were consistently high in the PFZ / IPFZ (average = 224 ind.m^{-3}). Abundance peaks were recorded in the ISAFZ, at the SAF-S, and to the south of the SAF-S (maximum = 744 ind.m^{-3}). Transect densities were lowest in the AZ-N (average = 31.14 ind.m^{-3}) but increased to the south of the SF-N (average = 292 ind.m^{-3}). Density peaks of up to 892 ind.m^{-3} and 620 ind.m^{-3} were recorded immediately to the north and south of the SB respectively.

4.3.4. Zooplankton Community Structure

4.3.4.1. Night Communities

Six spatially discrete sample clusters were identified by Cluster Analysis of night samples (Figure 4.5), generally characterized by distinct SST and SS values (Figure 4.6). Cluster 6 separated at ~ 60% dissimilarity and comprised samples from the AZ-N. Chlorophyll *a*, zooplankton abundance and average species richness in Cluster 6 were the lowest for any cluster (Table 4.2). No species numerically dominated total abundance, and this was reflected by the high average diversity. Only *Salpa thompsoni* had an IndVal $\geq$ 25% (Figure 4.7). Cluster 1, 2, 3, 4 and 5 samples remained ungrouped at 60% dissimilarity. Together these samples shared a number of taxa with high IndVals, including maximum values for foraminiferans and appendicularians, demonstrating their importance across most of the survey area (Figure 4.7).

Cluster 5 separated at ~ 56% dissimilarity and comprised samples at the SAF-N and in the SAZ (Figure 4.5). The wide spread of Cluster 5 samples in the SST / SS plot was a reflection of the steep gradients at the SAF-N (Figure 4.6). Chlorophyll *a* levels were relatively high but zooplankton densities were low (Table 2). Thirty one taxa were recorded but average sample species richness was low indicating that many taxa were patchily distributed. Indeed, inter-sample dissimilarity was highest within this cluster. Diversity was low, and abundance levels were dominated by foraminiferans and appendicularians. Both *Salpa thompsoni* and *Thysanoessa macrura / vicina* occurred at relatively high abundance. Eight taxa were unique to Cluster 5, including the copepods *Calocalanus* spp.,

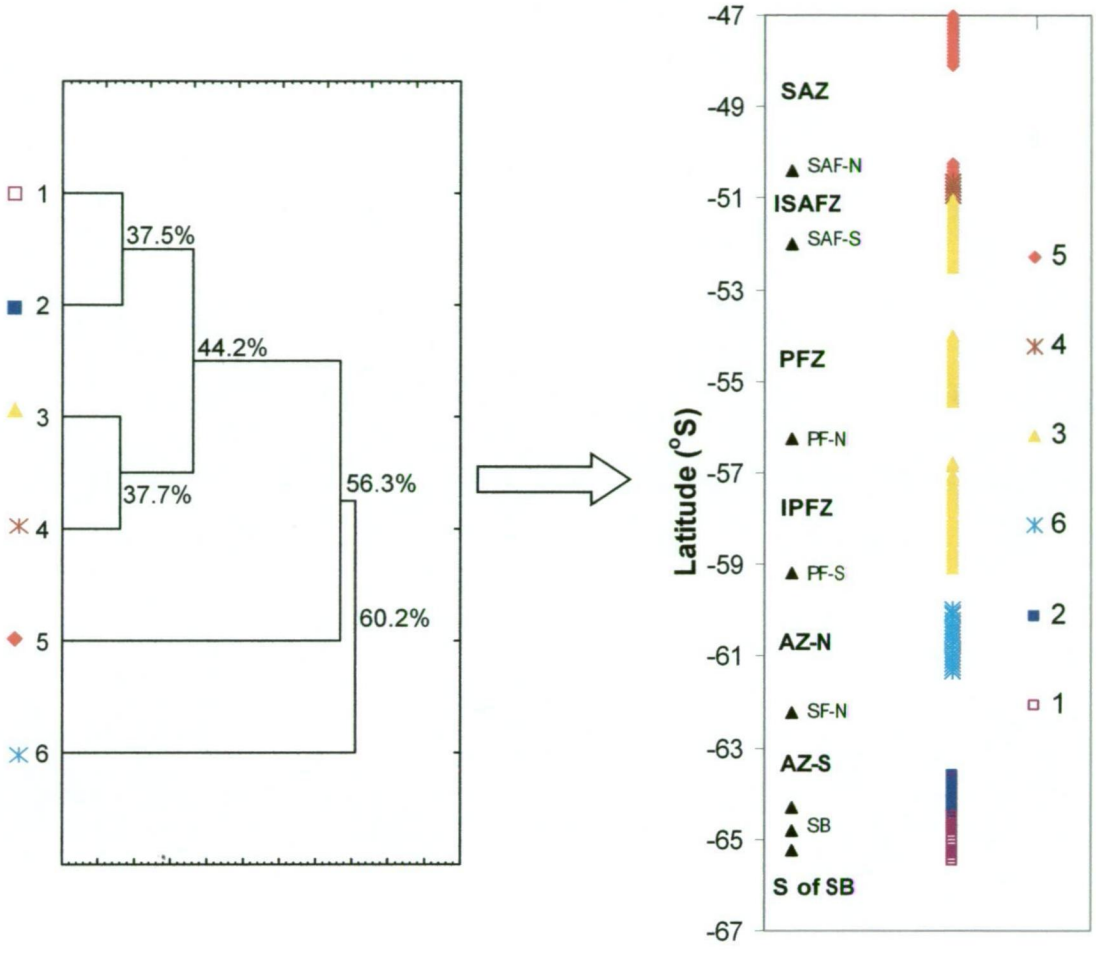


Figure 4.5. Results of the cluster analysis of **night** samples. The left hand panel illustrates the relationship between sample clusters, and the percentage dissimilarity between clusters at each level of separation. Due to the large number of samples (135) only cluster codes were illustrated in this diagram. The samples comprising each cluster, and their distribution along the 140°E transect line, are indicated in the right hand panel. The sample symbols and numbers in the right hand panel correspond with those of the sample clusters in the cluster dendogram. Fronts and inter-frontal zones along the 140°E transect line are indicated. Frontal positions are indicated by ▲ and correspond with Figure 4.2 (the AF-S and ASF are not labeled), while zones follow Table 4.1.

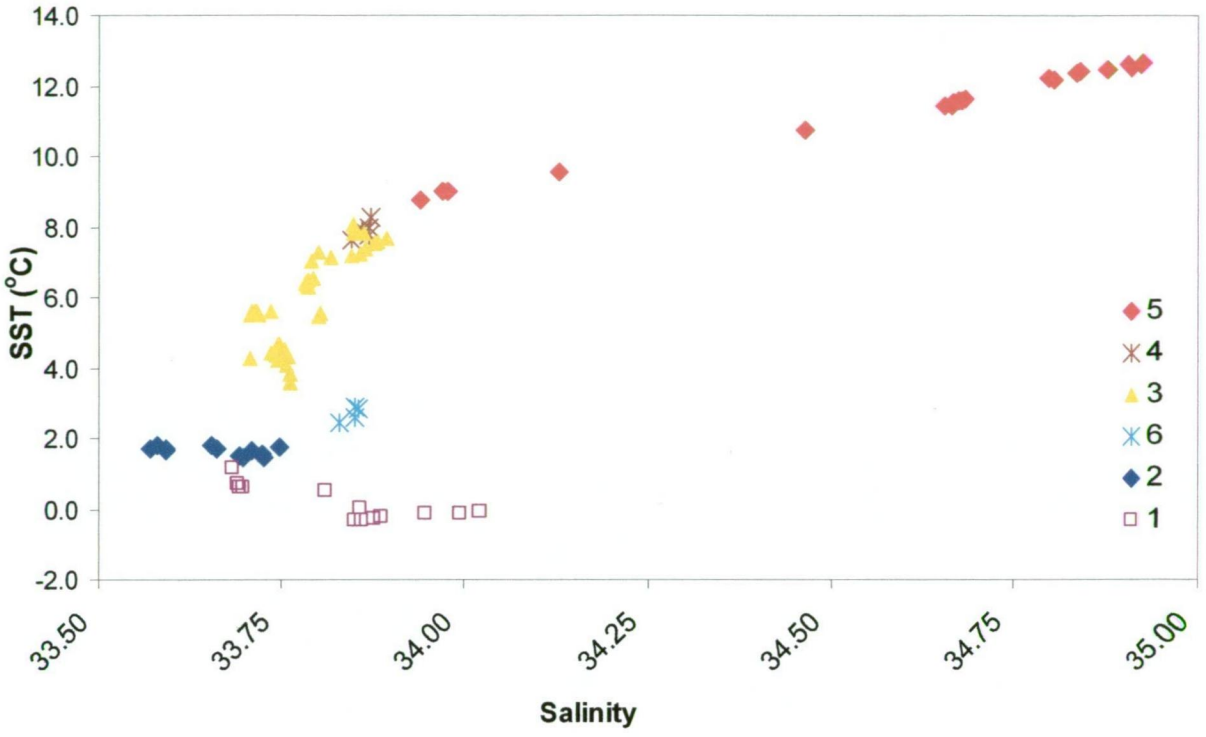


Figure 4.6. Plot of night CPR samples based on their average values of Sea Surface Temperature (°C) and Surface Salinity. Sample colour and number codes correspond with the clusters identified in Figure 4.5. Only four Cluster 6 samples are represented due to the gap in salinity data.

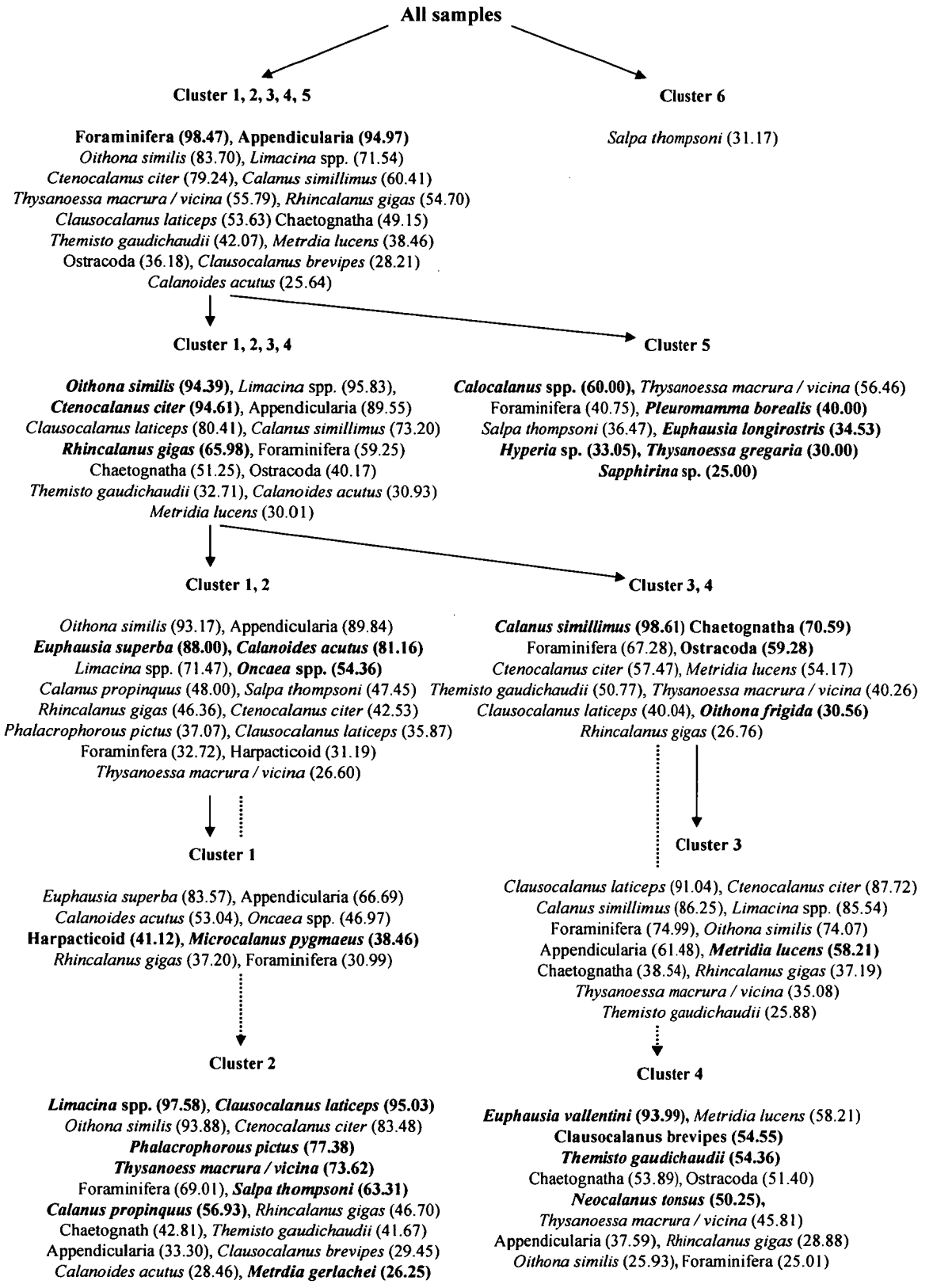


Figure 4.7. Results of the Indicator Value (IndVal) analysis (Dufrene and Legendre 1997) of **night** samples. IndVals were calculated at each level of separation in the cluster analysis (Figure 5). Only IndVals of ≥ 25 % were used, which meant that a taxon was present in ≥ 50% of samples in a cluster and that its relative abundance in that cluster was ≥ 50%. Maximum Indicator Values are in bold.

Overleaf:

Table 4.2. Average within cluster dissimilarity, chlorophyll *a* ($mg.m^{-3}$), taxon abundance ($individuals.m^{-3}$) levels, species richness and diversity for the six clusters identified by Cluster Analysis of **night** data. Significant differences between clusters were determined by ANOVA and Newman-Keuls multiple range tests. Abundance data were $log_{10}(x+1)$ transformed prior to analysis. Significantly higher values are underlined and in bold. The number of unique taxa and total taxa recorded per cluster are indicated. * $p<0.05$; ** $p<0.001$.

	C1 (n=13)	C2 (n=12)	C6 (n=18)	C3 (n=67)	C4 (n=5)	C 5 (n=20)	F	p
Within cluster dissimilarity (%)	24.31	14.32	35.39	24.89	19.09	39.10	No test	
Chlorophyll *a* (mg.m^{-3})	**0.69**	0.53	0.18	0.44	0.52	0.45	23.81	***
Total abundance (ind. m^{-3})	312.72	**691.67**	47.17	236.78	79.33	85.90	55.73	***
Species richness (r)	11.08	**14.17**	8.00	**12.96**	**13.40**	10.25	10.54	***
Diversity (H')	1.70	**2.31**	**2.62**	**2.33**	**2.68**	1.70	11.71	***
Code	**Taxon**							
Cal	*Calocalanus* spp.					0.93		
Pb	*Pleuromamma borealis*					0.57		
Sa	*Sapphirina* sp.					0.33		
Dl	*Dairella latissima*					0.07		
Pl	Platysceloidea					0.07		
Es	*Euphausia similis*					0.03		
Elu	*Euphausia lucens*					0.07		
Tgr	*Thysanoessa gregaria*					**0.47**	7.82	**
Ev	*Euphausia vallentini*				0.12	**1.87**	0.10	19.61	**
Nt	*Neocalanus tonsus*				0.13	**0.67**	0.07	3.70	**
El	*Euphausia longirostris*				0.01		**0.50**	8.92	**
Ml	*Metridia lucens*				**1.56**		0.37	9.59	**
Hy	*Hyperia* sp.				0.04		**0.47**	6.91	**
G	Gelatinous plankton				0.09		**0.27**	3.01	*
Pm	*Primno macropa*				0.02		0.03		
To	*Tomopteris* spp.			0.07	0.08		0.03		
Vi	*Vibilia* spp.		0.06		0.01		0.13		
Mp	*Microcalanus pygmaeus*	**0.36**			0.01		0.07	7.60	**
Pa	*Paraeuchaeta* spp.	0.10			0.24		0.03		
Tg	*Themisto gaudichaudii*		0.33	0.04	0.90	**1.07**	0.37	7.29	**
Cb	*Clausocalanus brevipes*	0.05	0.39		0.50	**1.07**	0.37	2.74	*
O	Ostracoda	0.05		0.07	0.82	**1.47**	0.10	11.82	**
F	Foraminifera	26.72	**59.50**	1.11	**91.54**	30.53	**52.10**	69.35	**
Li	*Limacina* spp.	3.49	**140.33**	5.59	21.11	3.20	0.37	92.33	**
Cc	*Ctenocalanus citer*	11.03	**55.72**	6.78	**46.69**	6.53	2.33	49.60	**
Os	*Oithona similis*	15.74	**241.44**	5.67	9.52	3.33	2.30	94.64	**
Tmv	*Thysanoessa mac / vic*	0.31	**2.33**	0.56	**1.19**	**1.60**	**3.77**	7.60	**
Ch	Chaetognatha	0.10	0.61	0.48	**1.71**	**2.00**	0.53	10.99	**
A	Appendicularia	**192.92**	**96.33**	1.48	17.04	10.27	5.27	54.84	**
St	*Salpa thompsoni*	0.26	**1.39**	0.70	0.01		**2.20**	11.72	**
Ha	Harpacticoid	0.36	0.11		0.04		0.03		
Of	*Oithona frigida*				0.30	0.13		4.53	**
Cs	*Calanus simillimus*			0.04	**14.22**	2.27		188.97	**
Rg	*Rhincalanus gigas*	**1.74**	**2.22**		**1.65**	0.93		9.69	**
Sm	*Scolecithricella minor*				0.22				
Et	*Euphausia triacantha*				0.02				
Ef	*Euphausia frigida*				0.08				
He	*Heterorhabdus austrinus*				0.01				
Cf	*Candacia falcifera*		0.11		0.09				
Pp	*Phalacrophorus pictus*	0.05	**0.67**		0.07			22.45	**
Ca	*Calanoides acutus*	**3.95**	**1.78**		0.11			29.43	**
On	*Oncaea* spp.	**0.82**	0.39		0.02			21.44	**
Cl	*Clausocalanus laticeps*	0.31	**5.89**	0.56	2.88			42.43	**
Mg	*Metridia gerlachei*	0.10	**0.38**					7.40	**
Cp	*Calanus propinquus*	0.26	**1.50**					30.47	**
Esu	*Euphausia superba*	**28.82**	5.67					62.67	**
Ec	*Euphausia crystallorophias*	0.21							
	Total taxa	22	22	14	36	16	31		
	Unique taxa	1			4		8		

Pleuromamma borealis and *Sapphirina* sp., the amphipods *Dairella latissima* and Platysceloidea, and euphausiids *Euphausia similis*, *E. lucens* and *Thysanoessa gregaria*, all of which are species with typically Temperate or Sub-Tropical distributions (Gibbons 1997, Bradford-Grieve et al. 1999, Vinogradov 1999). Also present was the SAZ copepod *Neocalanus tonsus* (Guglielmo and Ianora 1995), and *Euphausia vallentini*, which is characteristic of the SAZ and PFZ (Kirkwood 1982). IndVal analysis highlighted the importance of Temperate and Sub-Tropical taxa in Cluster 5 (Figure 4.7).

Samples from Clusters 1, 2, 3 and 4 remained grouped at ~ 56% dissimilarity. Together they had maximum IndVals for *Oithona similis*, *Ctenocalanus citer* and *Rhincalanus gigas,* while *Limacina* spp., appendicularians and *Clausocalanus laticeps* had IndVals > 80%, highlighting the importance of these taxa south of the SAF-N (Figure 4.7). Samples from Clusters 1 and 2 separated from Clusters 3 and 4 at ~ 44% dissimilarity (Figure 4.5). Clusters 1 and 2 comprised samples south of the SF-N (within the SIZ), and they were characterized by maximum IndVals for *Euphausia superba*, and the copepods *Calanoides acutus* and *Oncaea* spp., as well as the occurrence of *Metridia gerlachei* and *Calanus propinquus* (Figure 4.7; Table 4.2). Clusters 3 and 4 comprised samples from between the SAF-N and the PF-S and had maximum IndVals for chaetognaths, ostracods and *Oithona frigida* and *Calanus simillimus*.

Clusters 3 and 4 separated at 37.7% dissimilarity. Cluster 3 comprised the 65 samples located between the PF-S and the SAF-S, spanning ~ 9° latitude, and including the PFZ and IPFZ (Figure 4.5). SS had a narrow range while SST ranged from 3.59 to 8.10°C (Figure 4.6). Chlorophyll *a* and zooplankton abundance were relatively high, as were species richness and diversity (Table 4.2). Although thirty six taxa were identified only four were unique to Cluster 3, including *Euphausia triacantha, E. frigida, Heterorhabdus austrinus* and *Candacia falcifera*. Five species had the northern limits of their distribution in Cluster 3, amongst them *C. acutus*, *C. falcifera*, *P. pictus*, *Oncaea* spp. and *C. laticeps*. Foraminiferans, *C. simillimus* and *Metridia lucens* abundance levels were significantly higher in Cluster 3 than any other, while appendicularians, *C. citer*, *Limacina* spp., *O. similis*, ostracods, and chaetognaths were all important contributors to total abundance.

Cluster 4 comprised samples from the ISAFZ (Figure 4.5). A physical gradation was evident between Cluster 4 and the northern samples of Cluster 3 in the SST / SS plot (Figure 4.6). Chlorophyll *a* was high but zooplankton abundance was

low, being comparable to that in the SAZ (Table 4.2). Average species richness, diversity, and within cluster similarity were high, indicating a widespread distribution of taxa amongst samples. Foraminiferans, *E. vallentini*, *N. tonsus*, *Themisto gaudichaudii* and *Clausocalanus brevipes* were important components of the ISAFZ community (Table 4.2; Figure 4.7). Like *N. tonsus*, *C. brevipes* is a species characteristic of the SAZ (Errhif et al. 1997).

Clusters 1 and 2 separated at 37.5% dissimilarity. Cluster 2 comprised the low salinity, high chlorophyll *a* AZ-S samples (Figure 4.5 and 4.6; Table 4.2). Average species richness and within cluster similarity were high reflecting consistent community structure within this region (Table 4.2). Total zooplankton abundance averaged 692 ind.m^{-3} and included the highest abundance levels of *O. similis*, *Limacina* spp. and *C. citer*, as well as high densities of foraminiferans, appendicularians, *S. thompsoni*, *T. macrura / vicina*, *C. laticeps*, *P. pictus*, *C. acutus* and *C. propinquus*. The high densities and frequency of occurrence of these taxa were reflected by their IndVals (Figure 4.7).

Cluster 1 comprised samples south of the SB, including those on the continental slope (~ 65.50°S) (Figure 4.5). The latter fact was demonstrated by the presence of the neritic euphausiid *E. crystallorophias* (Kirkwood 1982) (Table 4.2). Surface water in this region was cold and more saline than samples in the AZ-S (Figure 4.6). Chlorophyll *a* levels were significantly higher than in any other cluster and zooplankton densities were high, however, species richness was intermediate and diversity was low (Table 4.2). Appendicularians dominated total abundance but Cluster 1 also had the highest densities of *E. superba*, *Oncaea* spp., and *C. acutus*. Harpacticoid copepods and *Microcalanus pygmaeus* both had maximum IndVals (Figure 4.7).

The sample clusters identified by Cluster Analysis were well reproduced by Correspondence Analysis (Figure 4.8a). By not classifying samples the Correspondence Analysis revealed a gradation in community characteristics between Clusters 2, 3, 4, 5 and 6, while Cluster 1 samples were strongly separated. The species associated with sample clusters (Figure 4.8b) largely reflected those identified by ANOVA and IndVal analysis (Table 4.2, Figure 4.7). Although Clusters 2 and 6 were strongly separated in the Cluster Analysis, Correspondence Analysis demonstrated that despite significant differences in abundance levels, they were characterised by a similar proportional representation of taxa. SST accounted for > 80% of the variation in the Dimension 1 and > 30% in Dimension 2, while SS

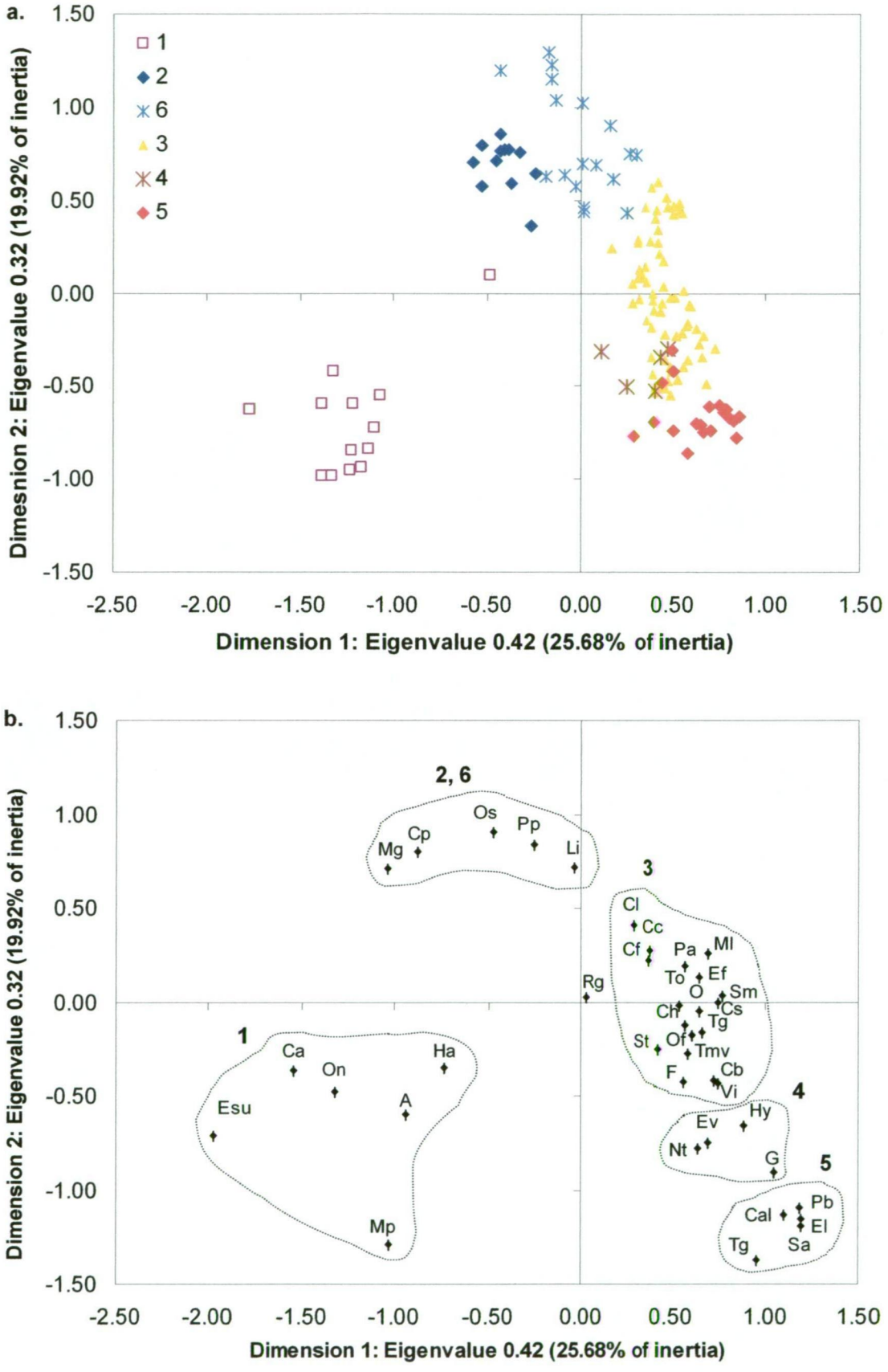


Figure 4.8. *legend overleaf…*

Figure 4.8. Ordination of **a.** samples and **b.** taxa using the first two dimensions of the Correspondence Analysis, based on taxa occurring in > 4% of **night** samples. Samples in **a** are colour / symbol coded to correspond with the six clusters identified by Cluster Analysis (Figure 4.5). Taxon codes in **b** follow those in Table 4.2, and taxon group numbers correspond with the numbers of sample clusters to which they are most closely associated.

Table 4.3. Results of second order polynomial regression of Sea Surface Temperature (°C), Surface Salinity and chlorophyll *a* ($mg.m^{-3}$) against the first two dimensions of the Correspondence Analysis: **a.** night **b.** day. * $p < 0.01$, *** $P < 0.0001$; NS indicates not significant.

a.	Dimension	R^2	Adjusted R^2	MS	F	p
SST (°C)	1	0.83	0.83	18.03	331.34	***
	2	0.34	0.31	6.98	31.68	***
Salinity	1	0.10	0.08	2.09	6.48	*
	2	0.51	0.51	7.53	62.49	***
Chlorophyll *a* ($mg.m^{-3}$)	1	0.34	0.33	7.26	33.42	***
	2	0.28	0.27	6.03	25.68	*

b.	Dimension	R^2	Adjusted R^2	MS	F	p
SST (°C)	1	0.69	0.68	17.55	107.76	***
	2	0.47	0.46	6.47	43.31	***
Salinity	1	0.21	0.20	5.47	13.27	***
	2	0.40	0.39	5.23	32.06	***
Chlorophyll *a* ($mg.m^{-3}$)	1	0.31	0.30	7.85	21.78	***
	2	0.05	0.03	0.65	2.42	NS

accounted for a small amount of variation in Dimension 1 but over 50% in Dimension 2 (Table 4.3a). Chlorophyll *a* was significantly correlated with both dimensions.

4.3.4.2. Day Communities

Five sample clusters were identified from the Cluster Analysis of day samples (Figure 4.9). Samples south of the PF-S (Clusters 1 and 2) separated from samples to the north (Clusters 3 to 5) at ~ 48% dissimilarity. The former had maximum IndVals for appendicularians and high values for *O. similis* and *Limacina* spp., while the latter had maximum IndVals for foraminiferans (Figure 4.11).

Clusters 1 and 2 separated at ~ 45% dissimilarity (Figure 4.11). Cluster 1 included all samples to the south of the SB and seven samples in the northern AZ-N. The spatial separation of the two sample groups within Cluster 1 was reflected by their physical properties (Figure 4.10). Average chlorophyll *a* was high in Cluster 1 but zooplankton densities and species richness were low (Table 4.4). *Oncaea* spp. and appendicularians were important community components (Table 4.4; Figure 4.9) but the samples south of the SB were characterised by the presence of *Euphausia superba*, while one AZ-N sample contained the copepod *M. lucens* indicating its affinities with the IPFZ. Cluster 2 comprised samples from the vicinity of the SF-N and one sample at the PF-S (Figure 4.9). Chlorophyll *a* levels and species richness were low while diversity was the highest for any cluster (Table 4.4). *Oithona similis*, *Limacina* spp. and *C. laticeps* were important community components (Table 4.4; Figure 4.11), as was the case with the AZ-S community in the night analysis (Cluster 2).

Cluster 3 comprised two sample groups, one from the vicinity of the PF-N and the other from the northern PFZ (Figure 4.9). Despite their spatial separation the two sample groups had similar SST and SS characteristics (Figure 4.10). Chlorophyll *a*, total zooplankton abundance and diversity were comparatively high, and species richness was the highest for any cluster (Table 4.4). Cluster abundance was dominated by foraminiferans, but *C. simillimus*, *C. citer*, *R. gigas*, chaetognaths and *Thysanoessa macrura / vicina* all occurred at their highest abundance levels and at high frequencies in Cluster 3 (Table 4.4; Figure 4.11). Cluster 3 was also characterized by the occurrence of *C. acutus*, *P. macropa* and *O. frigida*, none of which occurred in any other cluster.

Clusters 4 and 5 separated at ~ 33% dissimilarity. Cluster 4 predominantly comprised samples from within the PFZ, but included one sample from the SAZ (Figure 4.9). Although Cluster 4 samples were distributed between the two Cluster 3 sample groups their community characteristics were most similar to the SAZ samples of Cluster 5 (Figure 4.11). Both Clusters 4 and 5 were dominated by foraminiferans, which reached peak survey densities in the former (average = 236 ind.m^{-3}) (Table 4.4). The densities of taxa other than foraminiferans were low, and this was reflected by the low diversity recorded for both clusters. The importance of indicator species was highlighted by the single Cluster 4 sample from the SAZ being characterised by the presence of the Sub-Tropical copepod *Calocalanus* sp.. The SAZ samples of Cluster 5 were characterised by the presence of the Sub-Tropical / Temperate copepod *Sapphirina* sp., the Sub-Antarctic euphausiid *T. gregaria*, as well as the highest densities and IndVal of *Calocalanus* sp. (Table 4.4; Figure 4.11).

As for the night data, sample clusters identified by Cluster Analysis were well reproduced by Correspondence Analysis (Figure 4.12a), and taxa associated with sample clusters (Figure 4.12b) largely reflected those identified by ANOVA and IndVal analysis (Table 4.4, Figure 4.11). A relatively strong separation was evident between Cluster 1 samples located south of the SB and those located in the northern AZ-N. The seven Cluster 1 samples located in the northern AZ-N were largely distributed between Clusters 1 and 2, indicating a gradation in characteristics between these two communities, and appendicularians and *C. brevipes* were important community components. Cluster 4 and 5 samples demonstrated a high degree of similarity due largely to the high percentage contribution of foraminiferans to sample abundance. The comparatively large contribution of *Calocalanus* sp. to Cluster 5 samples (SAZ) resulted in their separation from Cluster 4. SST accounted for > 45% of the variation in first two dimensions of the ordination, and SS was significantly correlated with both dimensions, although not as strongly as SST (Table 4.3b). Chlorophyll *a* accounted for 30% of the variation in Dimension 1.

4.3.4.3. Zonal Zooplankton Group Structure and Diel Variation

Five community zones were common to both night and day data sets, and largely corresponded with the oceanographic zones of Table 4.1: South of the SB; AZ-S; AZ-N; IPFZ / PFZ; SAZ. An inter-zonal and night / day comparison of the

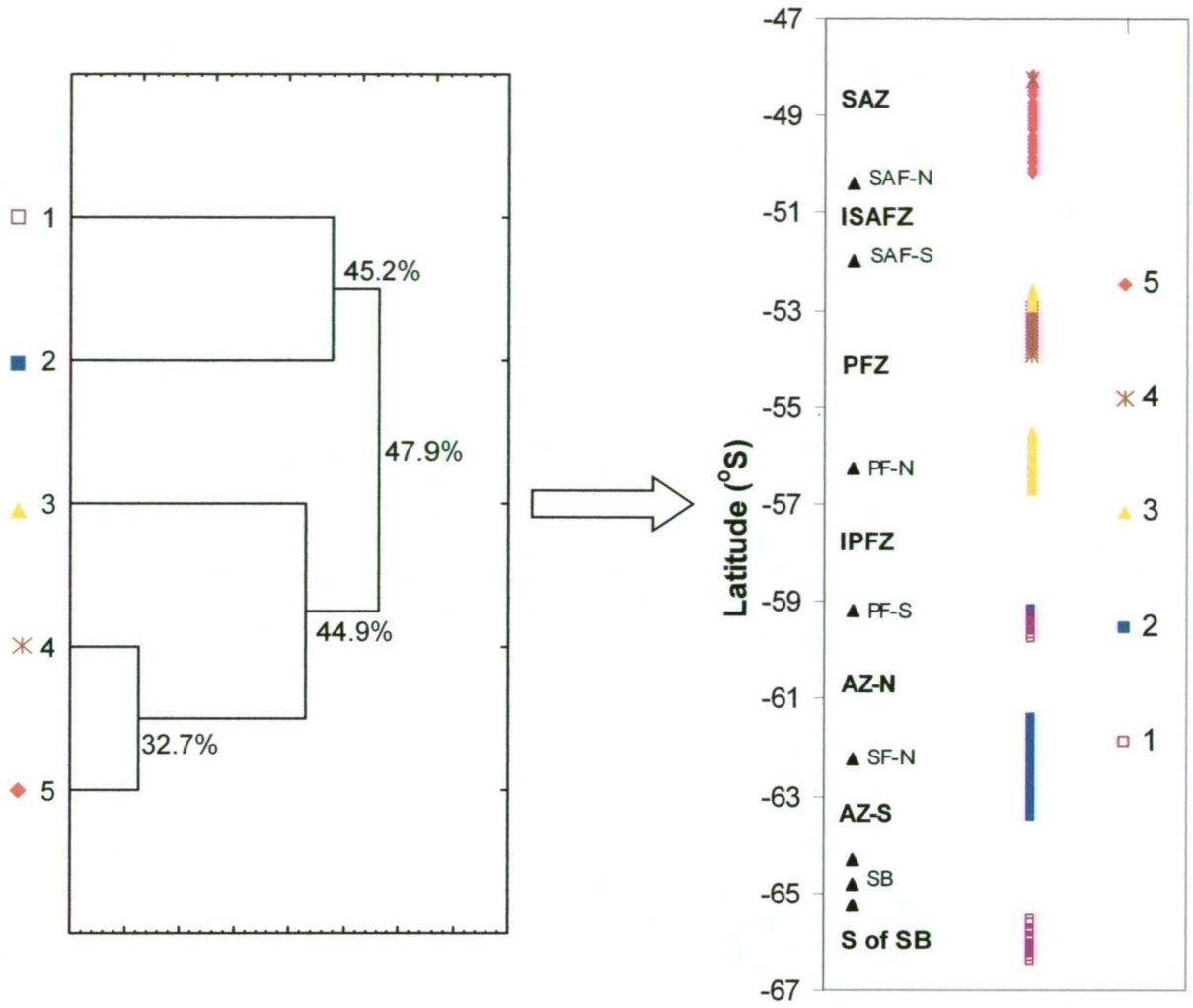


Figure 4.9. Results of the cluster analysis of **day** samples. The left hand panel illustrates the relationship between sample clusters, and the percentage dissimilarity between clusters at each level of separation. Due to the large number of samples (105) only the cluster codes were illustrated in this diagram. The samples comprising each cluster, and their distribution along the 140°E transect line, are indicated in the right hand panel. The sample symbols and numbers in the right hand panel correspond with those of the sample clusters in the cluster dendogram. Fronts and inter-frontal zones along the 140°E transect line are indicated. Frontal positions are indicated by ▲ and correspond with Figure 4.2 (the AF-S and ASF are not labeled), while zones follow Table 4.1.

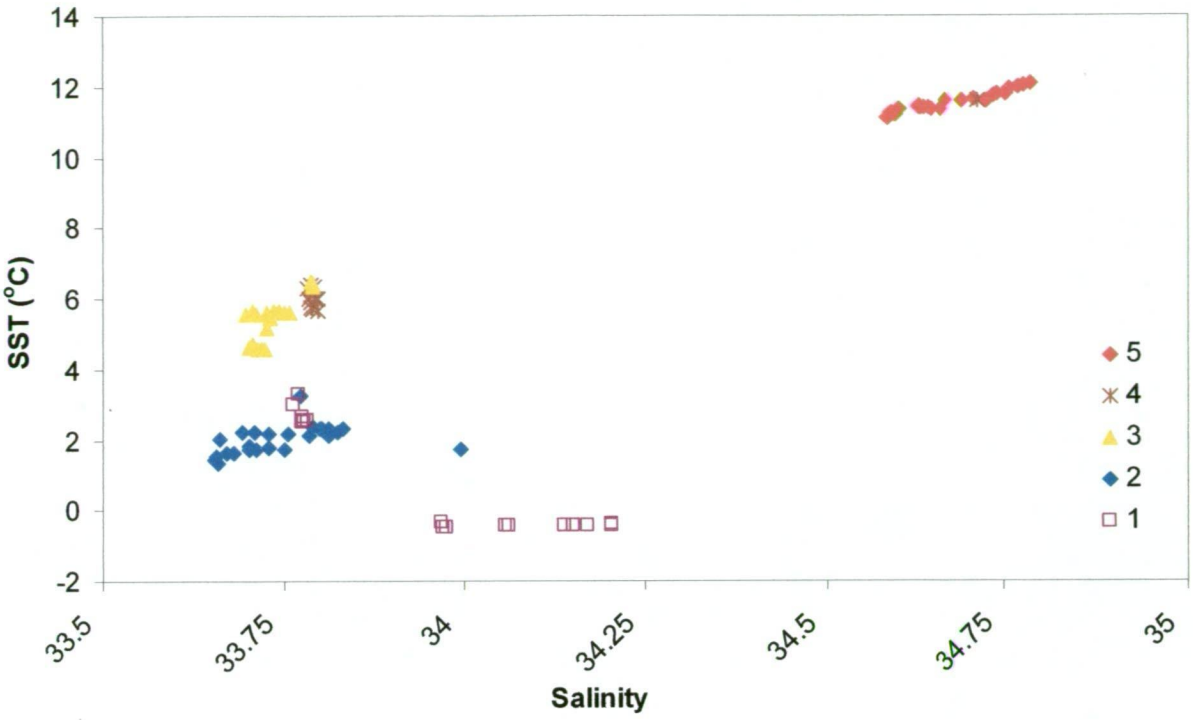


Figure 4.10. Plot of **day** CPR samples based on their average values of Sea Surface Temperature (°C) and Surface Salinity. Sample colour and number codes correspond with the clusters identified in Figure 4.9. One Cluster 1 sample had no SS data and was excluded from the plot.

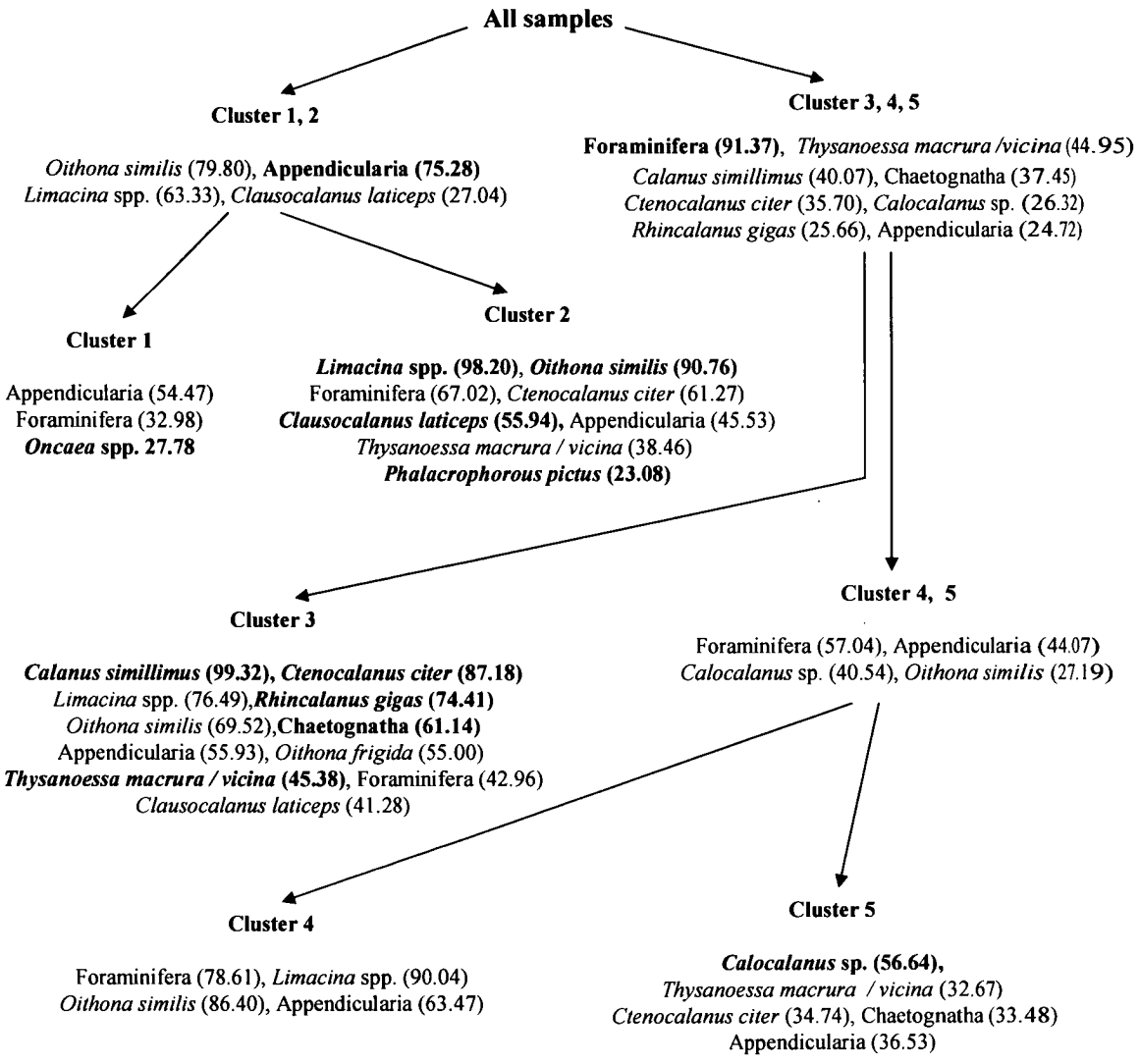


Figure 4.11. Results of the Indicator Value (IndVal) analysis (Dufrene and Legendre 1997) of **day** samples. IndVals were calculated at each level of separation in the cluster analysis (Figure 4.9). Only IndVals of ≥ 25% were used, which meant that a taxon was present in ≥ 50% of samples in a cluster and that its relative abundance in that cluster was ≥ 50%. Maximum indicator values are in bold.

Table 4.4. Average within cluster dissimilarity, chlorophyll *a* ($mg.m^{-3}$), taxon abundance ($individuals.m^{-3}$), species richness and diversity for the six clusters identified by Cluster Analysis of **day** data. Significant differences between clusters were determined by ANOVA and Newman-Keuls multiple range tests. Abundance data were $log_{10}(x+1)$ transformed prior to analysis. Significantly higher values are underlined and in bold. The number of unique taxa and total taxa recorded per cluster are indicated. * $p<0.05$; ** $p<0.001$.

	C 1 (n=18)	C 2 (n=26)	C 3 (n=20)	C 4 (n=14)	C 5 (n=23)	F	p
Within cluster dissimilarity (%)	31.55	27.69	23.64	15.80	23.36	No test	
Chlorophyll *a* ($mg.m^{-3}$)	0.28	0.21	**0.36**	0.26	**0.37**	7.67	***
Total abundance ($ind.m^{-3}$)	50.47	126.82	**163.03**	**263.71**	75.94	20.69	***
Species richness (r)	4.47	6.88	**9.80**	5.50	6.00	28.48	***
Diversity (H')	1.38	**2.10**	**1.89**	0.66	0.90	52.83	***
Codes	**Taxon**						
Sa	*Sapphirina* sp.				0.03		
To	*Tomopteris* spp.				0.12		
Tgr	*Thysanoessa gregaria*				0.06		
Cal	*Calocalanus* spp.			0.05	**0.64**	20.29	**
G	Gelatinous		0.17		0.09		
Rg	*Rhincalanus gigas*	0.04	0.10	**2.27**	0.03	21.43	**
Mp	*Microcalanus pygmaeus*	0.19			0.12		
Tg	*Themisto gaudichaudii*		0.05	0.17	0.10	0.09	
Tmv	*Thysanoessa mac / vic*		0.67	2.17	0.76	1.04	
Cc	*Ctenocalanus citer*	0.48	1.51	**7.80**	0.05	0.38	15.93	**
F	Foraminifiera	6.93	14.08	97.33	**236.00**	64.23	55.34	**
Li	*Limacina* spp.	0.41	**22.28**	5.33	3.67	0.41	52.21	**
Ch	Chaetognatha	0.04	0.21	**1.03**	0.10	0.32	8.74	**
A	Appendicularia	30.93	25.85	10.63	11.38	6.55		
Os	*Oithona similis*	4.41	**43.28**	6.00	5.52	0.87	23.17	**
Vi	*Vibilia* spp.				0.05		
Cs	*Calanus simillimus*		0.08	**18.33**	0.33		110.28	**
Cl	*Clausocalanus laticeps*	0.04	**1.18**	**0.60**	0.14		5.74	**
Cb	*Clausocalanus brevipes*	0.04	0.08	0.03	0.05			
St	*Salpa thompsoni*		0.08		0.19			
Ca	*Calanoides acutus*			0.03				
Of	*Oithona frigida*			1.07				
Pm	*Primno macropa*			0.10				
O	Ostracoda		0.05	**0.40**			2.76	*
On	*Oncaea* spp.	**0.30**		0.03			3.88	*
Ha	Harpacticoid	0.04		0.03				
Pp	*Phalacrophorus pictus*		0.18					
Esu	*Euphausia superba*	0.11	0.05					
Ml	*Metridia lucens*	0.04						
	Total taxa	**14**	**16**	**19**	**14**	**15**		
	Unique taxa	**1**	**1**	**3**	**1**	**3**		

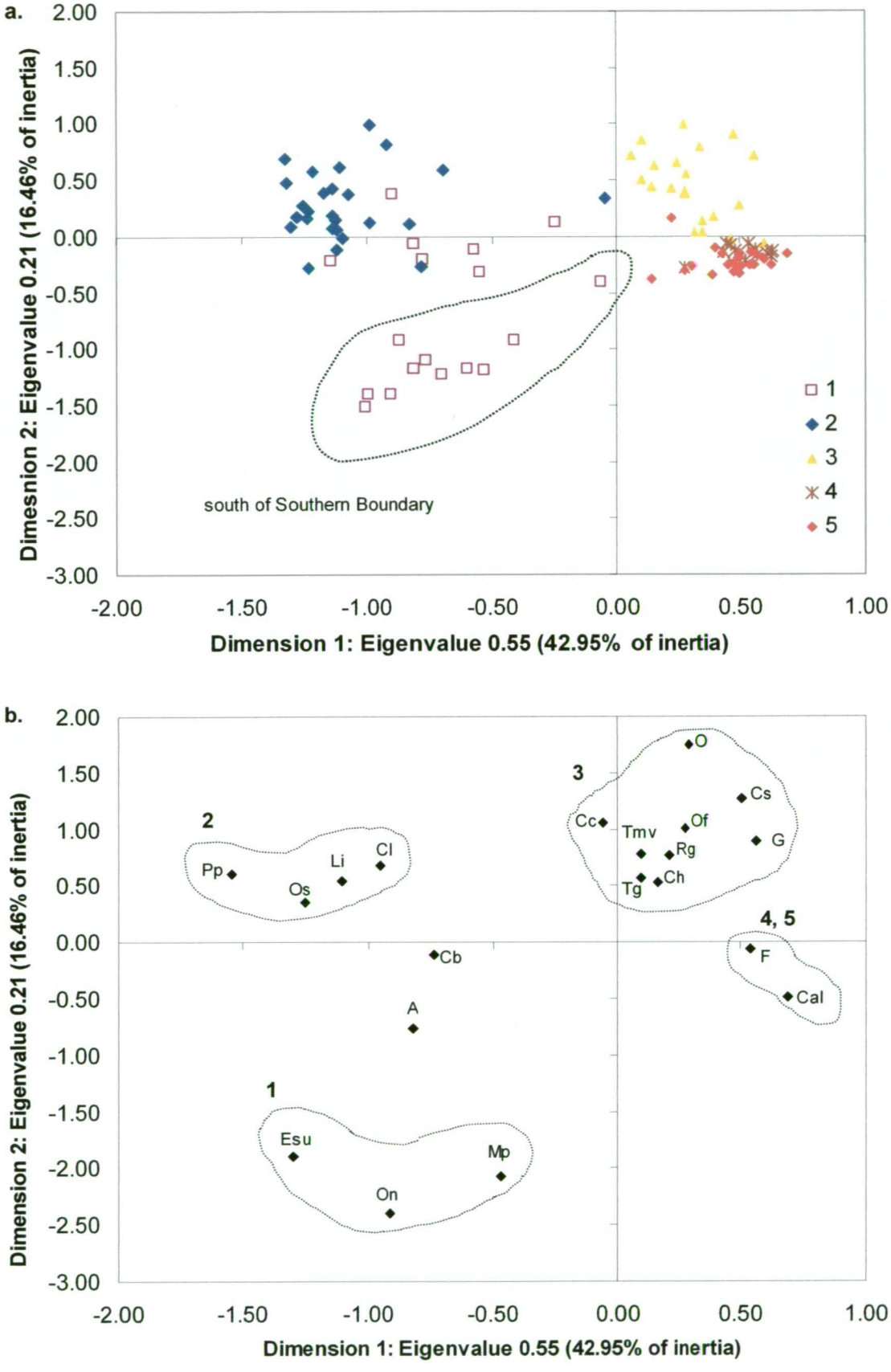


Figure 4.12. *legend overleaf…*

Figure 4.12. Ordination of **a.** samples and **b.** taxa using the first two dimensions of the Correspondence Analysis, based on taxa occurring in > 4% of **day** samples. Samples in **a** are colour / symbol coded to correspond with the five clusters identified by Cluster Analysis (Figure 4.9). Taxon codes in **b** follow those in Table 4.4, and taxon group numbers correspond with the numbers of sample clusters to which they were most closely associated.

major zooplankton groups was conducted. Due to the low occurrence of pteropod species' other than *Limacina* spp., the latter were grouped independently. Large calanoid copepodites (C1-3) and copepod nauplii were included in abundance calculations, the former being added to the group Large Calanoid Copepods. The two assemblages identified during the day between the PF-S and SAF-S were grouped together, and as a consequence some of their community specific characteristics were lost. The assemblage identified in the ISAFZ was excluded from the comparison as no day-time data were collected.

Most zooplankton groups showed a day-time decrease in abundance (Figure 4.13). The major exception was foraminiferans which appeared to undergo reverse migration in the PFZ / IPFZ and in the SAZ. This had the effect of maintaining day-time total abundance at night levels in these two zones. The day-time decrease in total abundance was particularly strong in the AZ-S and south of the SB. The latter region was strongly dominated by appendicularians (> 63% to total abundance), during both night and day (Figure 4.13 and 4.14). Due to the high abundance of *E. superba* larvae, euphausiids were an important group south of the SB relative to other regions, and large calanoid copepods, cyclopoids and foraminiferans also made a comparatively large contribution to abundance. Total abundance was highest in the AZ-S. *Limacina* spp., copepod nauplii, small calanoid copepods and cyclopoids all had maximum densities in this zone, and together with large calanoid copepods and appendicularians they contributed > 70% to total abundance during both night and day. Lowest zooplankton densities occurred in the AZ-N (Figure 4.13), however, the proportional contribution of groups to total abundance in the AZ-N was similar to that in the AZ-S (Figure 4.14), as reflected by the Correspondence Analysis. Foraminiferans were integral community components in the PFZ / IPFZ and the SAZ, contributing > 40% and > 75% to total abundance in day and night samples respectively. In the PFZ / IPFZ large and small calanoid copepods, and *Limacina* spp. made relatively large contributions to total abundance, while ostracods, hyperiids, and chaetognaths all occurred at high abundance levels. Small calanoid copepods were important community components in the SAZ. *Salpa thompsoni* occurred widely across the study area. High abundance levels were recorded in the AZ-S, IPFZ / PFZ and SAZ, while low levels were recorded south of the SB. The high standard deviations in the SAZ (Figure 4.13) demonstrated that the highest density patches occurred in this region.

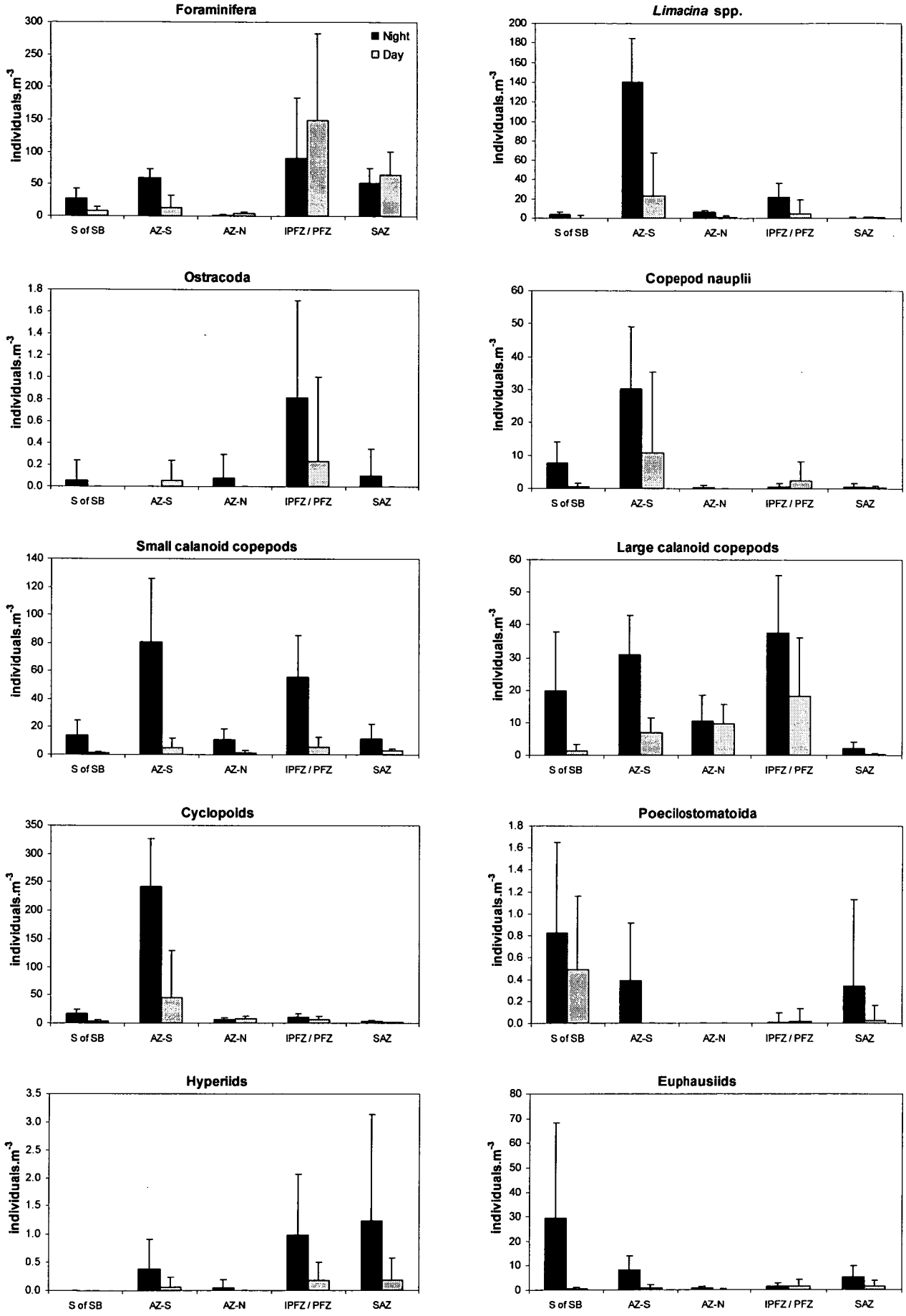


Figure 4.13. *continued overleaf...*

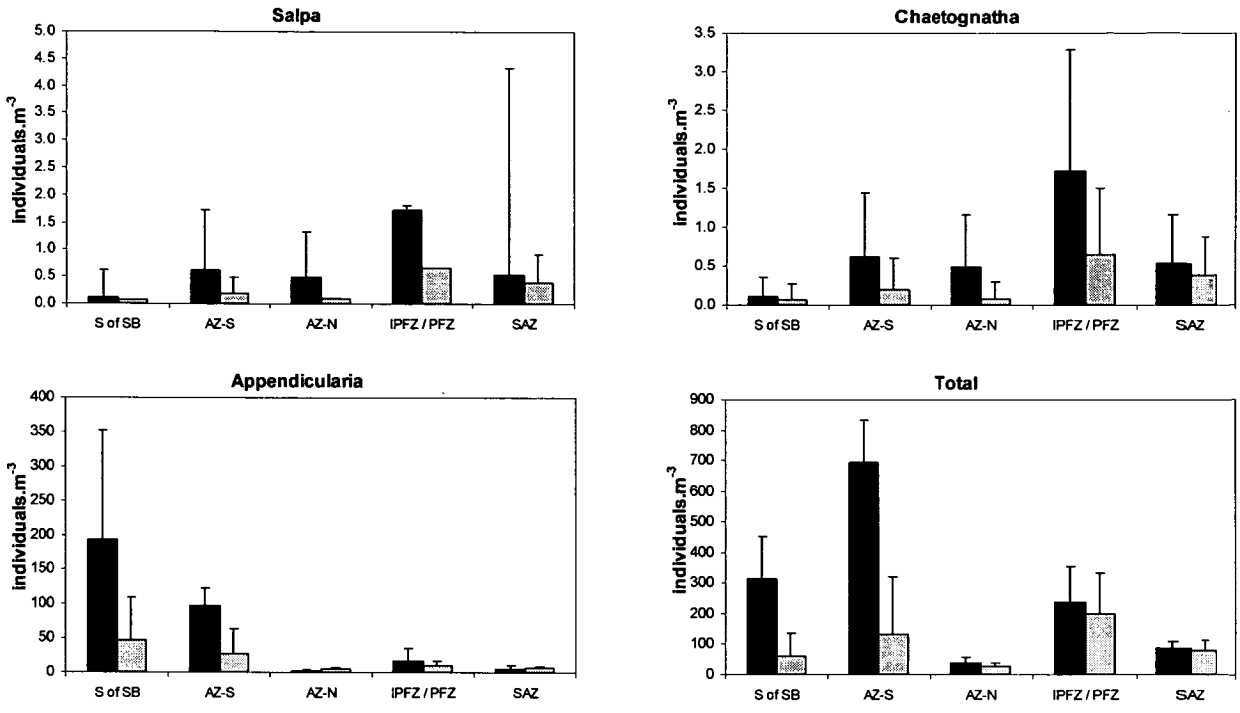


Figure 4.13. Abundance (individuals.m^{-3}) levels and standard deviations of major zooplankton groups during night (dark bars) and day (light bars) in five community zones identified from Cluster and Correspondence Analysis: South of the Southern Boundary (S of SB), the Southern Antarctic Zone (AZ-S), Northern Antarctic Zone (AZ-N), Polar and Inter Polar Frontal Zones (PFZ and IPFZ), the Sub-Antarctic Zone (SAZ). Zonal definitions follow those in Table 4.1.

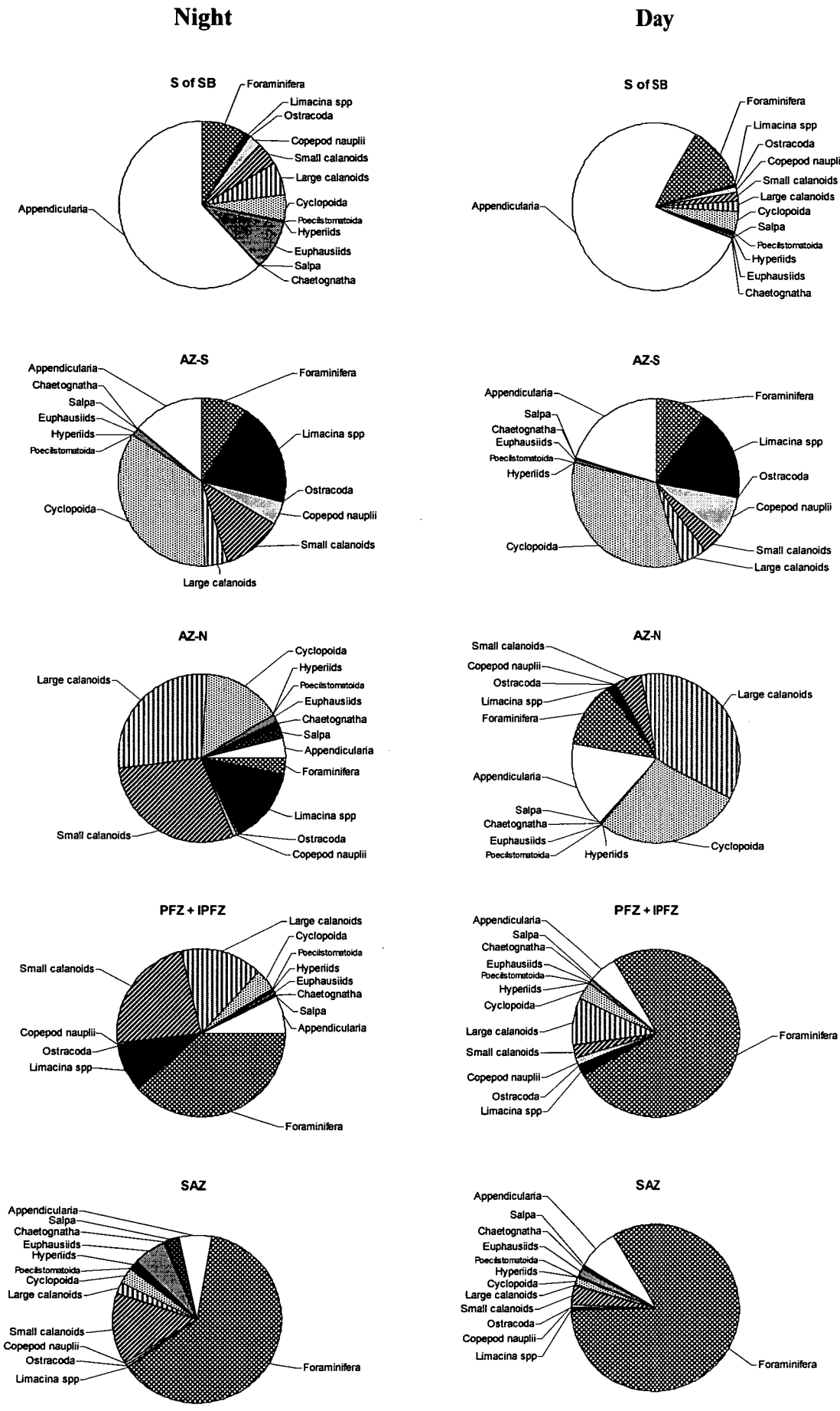


Figure 4.14. *Legend overleaf...*

Figure 4.14. Percentage contribution of major zooplankton groups to night and day samples in five community zones identified from Cluster and Correspondence Analysis: South of the Southern Boundary (S of SB), the Southern Antarctic Zone (AZ-S), Northern Antarctic Zone (AZ-N), Polar and Inter Polar Frontal Zones (PFZ and IPFZ), the Sub-Antarctic Zone (SAZ). Zonal definitions are presented in Table 4.1.

4.4. Discussion

The CPR transect completed between 25 February and 3 March crossed eight of the nine Southern Ocean fronts south of Australia, having ended to the south of the Sub-Tropical Front (STF) (Sokolov and Rintoul 2002). This transect therefore provided comprehensive coverage of the majority of oceanographic zones in the Southern Ocean south of Australia, and an excellent data base from which to assess the influence of physical zonation. Substantial diel variation was evident in community structure. Although night and day samples had many species in common, sixteen taxa occurred in the night samples that were completely absent during the day. These included *Neocalanus tonsus*, *Euphausia vallentini* and *E. longirostris*, important indicators of the ISAFZ and SAZ, and *Metridia gerlachei* and *Calanus propinquus*, indicators of the SIZ. The low number of taxa in day clusters with IndVals $\geq$ 25% highlighted the low frequency of occurrence and low abundance of many taxa in the day samples. Many taxa that were zonally widespread at night occurred in fewer zones during the day e.g. *Metridia lucens*, *Tomopteris* spp., *Vibilia* spp., ostracods, *Salpa thompsoni* and *Phalacrophorus pictus*. However, despite diel differences, the night and day data sets demonstrated similar community zonation.

4.4.1. Sub-Antarctic Zone and Inter Sub-Antarctic Front Zone

The importance of the SAF as a biogeographic barrier demonstrates considerable circumpolar variability. A distinct SAZ community has been identified in the south Atlantic and Pacific Ocean south of New Zealand (Tarling et al. 1995, Pakhomov and McQuaid 1996, Atkinson and Sinclair 2000). However, the influence of the SAF in the Indian Ocean south of Africa is less clear, and if anything appears to be weak (Pakhomov and McQuaid 1996, Pakhomov et al. 2000). Furthermore, in those studies where a distinct SAZ community was recognized, differences to the PFZ were predominantly due to variations in the abundance of species occurring in both zones rather than differences in species composition. By contrast, in this study the SAF-N, with its steep SST and SS gradient, represented a sharp biogeographic barrier. Although sharing a number of widespread taxa with the waters to the south, the SAZ community was strongly differentiated, principally due to a large Temperate / Sub-Tropical taxonomic component, evident in both night and day

samples. The SAF-N represented the southern limit in the distribution of most of these taxa. By contrast, Temperate / Sub-Tropical taxa have been shown to be important components of the PFZ in the Southern Ocean south of Africa (Pakhomov et al. 2000). In this study the SAF-N was also the northern distributional limit of *Calanus simillimus*, and *Rhincalanus gigas*. The low zooplankton densities recorded in the SAZ appear to be a characteristic feature of this region (Errhif et al 1997, Takahashi et al. 1998).

The SAF-S was a relatively minor physical gradient in comparison to the SAF-N, resulting in a weak physical separation between the ISAFZ and northern PFZ samples. However, a second community was identified in the ISAFZ, supporting observations made from vertical net samples collected along the 140°E transect earlier in the season (Chapter 3, Hunt and Hosie 2003). Some southern taxa did not occur north of the SAF-S, including *Calanoides acutus* and the important PFZ species *Clausocalanus laticeps*. Overall, however, cluster analysis showed a high degree of similarity between the ISAFZ and PFZ / IPFZ communities, demonstrating that the SAF-S was a weaker biogeographic boundary than the SAF-N, equivalent to the SAF in other sectors of the Southern Ocean.

Apart from frontal structure two modes of water transport are likely to have influenced the community relationships between the SAZ / ISAFZ / PFZ. The first of these is poleward water transport by eddy shedding (Philips and Rintoul 2000). However, eddy production is relatively low at 140°E due to frontal stability, increasing downstream (to the east) due to higher frontal instability and meandering (Sokolov and Rintoul 2002). A second mode of water transport along 140°E is the northward transport of surface water from the PFZ into the SAZ, over the top of Sub-Antarctic Mode Water (200m to 600m) (Rintoul and Trull 2001). This would facilitate the transport of PFZ taxa into the SAZ. The relatively important role of PFZ and widespread taxa in structuring the relationship between SAZ / ISAFZ / PFZ communities, in comparison to characteristic SAZ / Sub-Tropical taxa, indicates that the latter is the predominant mode of taxonomic exchange between these three zones.

4.4.2. Polar Frontal Zone and Inter-Polar Frontal Zone

The PF-N represented a weak biogeographic boundary in this study with a single zooplankton community being identified between the SAF-S and the PF-S,

embracing both the PFZ and IPFZ (a distance of ~ 400nm). The similarity of the PFZ and IPFZ communities therefore reflected the physical homogeneity of the region between the SAF-S and the PF-S. The PFZ / IPFZ was the centre of abundance of *C. simillimus* and *M. lucens*, and was characterised by the presence of a number of zonally unique taxa, including the PF indicator species *Euphausia triacantha* (Kirkwood 1982). The PFZ / IPFZ was also the northern distributional limit of a number of species with abundance maxima to the south of the SF-N. However, although showing affiliation with communities to both the north and south, the PFZ / IPFZ was most closely related to the ISAFZ.

An important observation from the PFZ / IPFZ day samples was the occurrence of two communities, one with night characteristics (high contribution of copepods and *T. macrura / vicina* to total abundance) and the other with day characteristics (low contribution of copepods and *T. macrura / vicina* to total abundance). Radiation levels recorded with these two communities were very similar, averaging 460.78 and 576.35 $\mu mol.s^{-1}.m^{-2}$ respectively. The day-time occurrence of the high abundance community has two implications. Firstly, that vertical migration is probably the dominant source of diel variation in zooplankton densities in CPR samples, rather than avoidance. Secondly, that diel migration may be influenced by factors other than radiation levels. Significantly higher chlorophyll *a* concentrations in the samples with high densities of copepods and *T. macrura / vicina* suggests that this may have been the driving force behind their day-time occupation of surface waters. The accumulation of zooplankton biomass in response to high phytoplankton biomass has previously been observed at South Georgia island (Atkinson et al. 1996). Concomitantly, the significantly higher chaetognath densities associated with the high copepod densities support observations from the 1926 deployments of the CPR in the Drake Passage, during the Discovery Expeditions (Hardy 1936b).

Both the PF and PFZ have been noted as regions of enhanced phytoplankton and zooplankton densities in other sectors of the Southern Ocean (Lutjeharms et al. 1985, Bathmann et al. 1997, Abbott et al. 2000, Atkinson and Sinclair 2000, Dubischar et al. 2002, Pollard et al. 2002, Read et al. 2002). The PF of the aforementioned studies corresponds with the PF-N in this study (defined by the northern limit of θ_{min} water cooler than 2°C). In this study only weak enhancement of chlorophyll *a* biomass was observed in the vicinity of the PF-N, SAF-S, and SAF-N. No strong peaks in zooplankton density were observed at the PF-N or PF-S, but

peaks were observed in the vicinity of the SAF-S. The weak biogeographic boundary of the PF-N, and apparent absence of density enhancement, indicates that this front is of less biological importance along 140°E than in regions such as the south Atlantic.

Although no strong peaks in zooplankton densities were observed in the PFZ / IPFZ, levels were consistently higher than in the SAZ and AZ-N. A plot of all CPR samples collected since 1997, under the auspices of the Southern Ocean CPR Survey, demonstrated that this is a consistent feature of the region (Hosie et al 2003). Greater than 50% of zooplankton collected on the transect were located within the PFZ / IPFZ, in both night and day samples, highlighting the importance of this region along 140°E. Calanoid copepod abundance was high, being equivalent to levels in the SIZ, however, foraminiferans were numerically the most important community component, as was the case in the two zones to the north (ISAFZ and SAZ).

4.4.3. Northern Antarctic Zone

Day samples from the AZ-N were grouped with those to the south of the SB by cluster analysis. However, this similarity was probably influenced by day-time migration of zooplankton out of the surface waters south of the SB, as analysis of the night data revealed a strongly differentiated community in the AZ-N. The night AZ-N community was characterised by low densities of common taxa and the absence of numerous indicator species present in the PFZ / IPFZ and AZ-S. The latter pointed to a strong biogeographic influence of the fronts bounding the AZ-N. The northern boundary of the AZ-N is determined by the PF-S. The strong SST signal associated with this front indicated a sharp physical separation of the AZ-N from the PFZ / IPFZ. The southern boundary of the AZ-N corresponds with the SF-N and thus, concurrently, the maximum winter sea-ice extent (Worby et al. 1998). The close coupling of sea-ice extent and ocean currents in this region indicates that there is little movement of surface water from south of the SF-N into the AZ-N (Heil and Allison 1999, Nicol et al. 2000a,c). The AZ-N is therefore strongly separated, physically, from the zones to the north and south.

However, the AZ-N community may have been affected by factors other than frontal separation. A number of widespread taxa had discontinuous distributions, being absent from the AZ-N but occurring in the zones to the north and south. Total

zooplankton densities decreased to their lowest levels in the AZ-N, and low densities were reflected by most taxa (large and small) indicating that this was not an artefact of under-sampling. Similarly, chlorophyll *a* biomass was lowest within the AZ-N, and Trull et al. (2001b) showed that low levels are a consistent feature of this zone. It is expected that low phytoplankton biomass would have influenced the low zooplankton densities in the AZ-N. A persistent feature of the Southern Ocean along 140°E is the occurrence of a sub-surface chlorophyll *a* maximum, developing in spring / early summer and persisting till late summer (Wright and van den Enden 2000, Parslow et al. 2001, Trull et al. 2001b). Optical Plankton Counter data has demonstrated that the vertical distribution of Southern Ocean zooplankton can be strongly correlated with phytoplankton biomass (Read et al. 2002). It is possible that the combination of a deep chlorophyll maximum and low surface chlorophyll *a* levels in the AZ-N served to concentrate zooplankton abundance, as well as some taxa, below the sampling depth of the CPR. Higher surface densities were recorded in this zone in early December (Figure 3.9), when the presence of diatoms on the CPR silks indicated that surface chlorophyll *a* biomass may have been higher than in late February. However, these relatively high densities may have been influenced by the diatoms increasing the sampling efficiency of the 270μm mesh. Further data are required to establish whether low species richness and densities of surface communities are consistent features of the AZ-N.

4.4.4. Southern Antarctic Zone and South of the Southern Boundary

The samples collected south of the SF-N fell within the SIZ, and were characterised by the occurrence of the zonally specific, stenotypic species *Calanus propinquus*, *Metridia gerlachei* and *Euphausia superba*. Although samples from this region demonstrated a high degree of similarity in species composition, two distinct communities were identified. The first comprised samples from the AZ-S, while the second comprised samples south of the SB. Differences between these communities were based almost entirely on variations in the abundance levels of shared taxa. However, despite their similarity in species composition, the boundary between the AZ-S and S of SB was sharp and strongly associated with the SB.

The AZ-S community was dominated by high densities of *O. similis*, *C. citer*, appendicularians and foraminiferans. South of the SB, within the colder and more saline waters of the Coastal Current, the community was dominated by

appendicularians. Copepods were relatively scarce but *E. superba* was significantly more abundant than in the AZ-S, a distribution previously noted by Nicol et al. (2000a,c). Two similar community types were identified in a previous study off the east Antarctic coast, although a high contribution of appendicularians was not observed in the "cold water" group (Chiba et al. 2001). Chiba et al. (2001) proposed that the abundance of small copepods is more strongly influenced by water temperature than phytoplankton biomass. This was supported here by the low densities of small copepods south of the SB in comparison to the AZ-S, despite high chlorophyll *a* biomass both to the north and south of the SB. However, ecological processes can not be excluded. Atkinson et al. (2001) hypothesized that *E. superba* may exert top-down control on copepod abundance in the South Georgia ecosystem. Although the CPR does not give a good indication of post-larval *E. superba* densities, larval densities (up to 130 ind.m^{-3}) pointed to a relatively high abundance of this species south of the SB.

SIZ chlorophyll *a* biomass was particularly high in the vicinity of the SB, lending support to the proposed ecological importance of this front (Tynan 1998). However, the distribution of zooplankton density peaks on either side of the SB chlorophyll *a* peak suggests that grazing may have been responsible for the observed distribution pattern. The large-scale "BROKE" survey, conducted in 1996, demonstrated that the majority of chlorophyll *a* biomass in east Antarctica was distributed to the south of the SB (Strutton et al. 2000). SeaWiFS data collected during the summer season corresponding with this study concurred with Strutton et al. (2000), identifying extremely high chlorophyll *a* biomass in the vicinity of 140°E, concentrated in the coastal zone (Hirawake et al. 2003). During the season this coastal biomass was transported northwards across the SB in eddies generated by northward excursions of the coastal current due to local bathymetry (Wakatsuchi et al. 1994). The coastal waters may therefore have been an important source of high offshore chlorophyll *a* biomass, providing a link between the offshore and onshore ecosystems.

4.4.5. Determinants of Zonal Structure

The taxa in this study generally had broad distributions. Most occurred in adjacent communities and only a few occurred in a single zone. This is a typical feature of the zooplankton. Individual species are seldom faithful to a single water

mass (physical zone), generally having a core region, but being widely distributed to regions beyond their reproductive range (Angel 1998). Of the 356 copepod species recognized in the Antarctic 16.5% (57 species) are endemic (Razouls et al. 2000). The remaining 289 species are considered cosmopolitan. Despite the multi-zonal distributions of many species, community boundaries in this study were generally sharp, and bounded by particular fronts. At least part of this correlation stemmed from the direct influence of the environment on species distributions. Zooplankton taxa have specific physical requirements. These requirements may be met by more than one zone. Due to the relative homogeneity of inter-frontal zones the distribution limits are most likely to coincide with the fronts themselves. The strikingly sharp nature of community boundaries identified by the CPR may be a function of its sampling in the horizontal. In the Southern Ocean both the horizontal and vertical structure of the water column are strongly stratified, although on spatial scales differing by an order of magnitude (Sokolov and Rintoul 2002). Horizontal stratification occurs over tens of miles while vertical stratification occurs over hundreds of meters. By sampling horizontal physical gradients, and aided by its higher sampling resolution, horizontal patterns in community structure may be more readily defined from CPR samples. Conversely, the identification of horizontal patterns in community structure by vertical and obliquely towed nets is complicated by their integrating vertical physical variation on each haul. This may be responsible for the less pronounced cross frontal community gradients observed in studies using these net systems (Deacon 1982, Hopkins et al. 1993, Tarling et al. 1995, Chiba et al. 2001).

The physical environment therefore directly influenced community structure through its influence on species composition. A measure of indirect control is also expected to have occurred. Latitudinal variations in vertical mixing, nutrients and light levels result in regionally specific and seasonally variable primary production regimes and phytoplankton communities in the Southern Ocean (Treguer and Jacques 1992, Mengesha et al. 1998, Trull et al. 2001b). Although no quantitative data on phytoplankton community composition were available, zooplankton communities and densities were significantly correlated with chlorophyll *a* biomass. Zooplankton have species specific dietary preferences (Perissinotto 1992, Atkinson 1994), while phytoplankton densities have been shown to influence both zooplankton densities and their depth distributions (Nicol et al. 2000a, Atkinson et al. 2001, Read et al. 2002). In the light of the latter point, the sub-surface summer /

autumn chlorophyll *a* maximum observed in the study area may result in severe density underestimates by the CPR both regionally and seasonally.

Differences in phytoplankton community structure may also have influenced the zooplankton communities sampled through alteration of the sampling efficiency of the 270μm mesh used in this study, and particularly a reduction in mesh size associated with high diatom densities. Anecdotal evidence for this was provided in Chapter 3 (Section 3.4). The high occurrence of diatoms in the SIZ CPR samples almost certainly reduced the diameter of the 270μm mesh, and would thus have contributed to the high densities of small copepods (particularly *O. similis*) recorded in the SIZ. As all SIZ samples were affected by the presence of diatoms, reduced mesh size would not have influenced the separation of the two SIZ communities observed on either side of the SB, but may have played a role in the separation of SIZ and open ocean communities. Densities of *O. similis* were low in both the AZ-N and IPFZ, after the relatively high levels (up to 140 ind.m^{-3}) recorded in December 2001 (Figure 3.9). As noted in Chapter 3 the December samples were characterised by the presence of diatoms, but this was not the case for the open ocean samples collected in late February / early March (this chapter).

The CPR itself, through its unique sampling characteristics, would have influenced the communities observed over the length of the transect (Chapter 3, Hunt and Hosie 2003). Many species occupy depth ranges below that sampled by the CPR (~ 10.5m), accounting for the low abundance of species such as *M. pygmaeus* in this study (e.g. Bradford-Grieve et al. 1999, Atkinson and Sinclair 2000), while the depth distribution of other taxa varies spatially (Duro et al. 1999). Many taxa undergo ontogenetic migrations introducing a seasonal component to their occupation of the surface waters (Voronina et al. 1978, Schnack-Schiel and Hagen 1994). A temporal effect on CPR samples may also be introduced by the seasonal cycle of population stage structure, with earlier (smaller) stages being less effectively sampled (Atkinson 1998). Both of these seasonal aspects have a spatial component due to latitudinal (horizontal) variation in the timing of population cycles (Voronina 1972). Seasonal variation therefore has important implications for zonal community structure at any moment in time.

4.4.6. Conclusions

The sector of the Southern Ocean south of Australia is oceanographically complex, being characterised by multiple branches of the Sub-Antarctic Front, Polar Front and Southern Front. Multivariate analysis of CPR samples identified a complexity in the zooplankton community structure which strongly reflected that of the oceanographic environment. Six zonally distinct communities were identified, two more than in an equivalent study (using vertical nets) south of Africa (Pakhomov et al. 2000), demonstrating the occurrence of circumpolar variation in Southern Ocean community structure and zonation, and highlighting the need for regionally specific studies in order to gain a complete understanding of this ocean's ecosystems. The boundaries between the six communities were typically sharp and correlated with fronts, demonstrating both the importance of fronts as biogeographic boundaries and the sensitivity of zooplankton to the physical environment. Although zooplankton communities were strongly structured by zonal differences in water mass properties, they also appeared to be influenced by phytoplankton regimes and mesoscale intra-zonal processes (e.g. eddy shedding, cross-frontal advection). The sensitivity of the zooplankton to cross-frontal physical variation clearly demonstrated their value as indicators of environmental change in long-term monitoring programs. Changes in the distributions of zonally specific species and assemblages, as well as changes in the composition of communities, are all potential ecological indications of a changing physical environment. However, in order to fully understand the implications of such ecological changes it is important that we establish the degree of natural variability, particularly seasonal and inter-annual cycles.

Chapter 5

Zooplankton community succession in the Seasonal Ice Zone off the Adelie Coast, east Antarctica

5.1. Introduction

5.1.1. Seasonal Cycles

Seasonal cycles are a major component of both spatial and temporal variability in zooplankton communities, influencing inter-zonal variation at a moment in time, and intra-zonal variation over the course of a season (Section 4.4.6). Data on seasonal variability provides a temporal context for the single voyage, short duration studies that predominate in Southern Ocean research. A detailed knowledge of seasonal cycles, and particularly the relationship between the biotic and abiotic components, can provide primary insights into long-term interactions between zooplankton and the environment (Reid et al. 1983, Planque et al. 1997, Beaugrand et al. 2001). Furthermore, changing seasonality has been identified as one of the most important aspects of long-term ecological change (Broekhuizen and McKenzie 1995, Planque and Fromentin 1996). An understanding of seasonal cycles is therefore fundamental to ecosystem monitoring. Seasonal cycles also have ecosystem level implications. The impact of zooplankton on ecosystems, e.g. grazing (Dubischar and Bathmann 1997, Mayzaud et al. 2002) and vertical flux (Smetacek et al. 1990, Gonzalez and Smetacek 1994, Verity and Smetacek 1996, Marine Zooplankton Colloquium 2001, Dubischar and Bathmann 2002, Dagg et al. 2003, Priddle et al. 2003), is strongly dependent on community structure. Seasonal community successions therefore introduce a temporal component to ecosystem functioning.

However, due to the logistics involved with ship based surveys in the Southern Ocean few seasonal studies have been undertaken, while those that have been completed have relied upon splicing together voyages conducted over a number of years (e.g. Siegel and Piatkowski 1990, Zmijewska 1993, Schnack-Schiel and Hagen 1994, Schnack-Schiel and Mizdalski 1994, Ward et al. 1997). These studies were therefore influenced by inter-annual variability in zooplankton community structure (Park and Wormuth 1993, Atkinson 1998, Takahashi et al.

1998, Chiba et al. 2001). Between October 2001 and March 2002 an Australian-Japanese collaborative study, employing four ships, performed multiple transects along the 140°E meridian south of Australia. Although the major purpose of this study was to investigate the physical-biological seasonality of the Seasonal Ice Zone (SIZ), all passes of the transect line extended northwards to 47°S (Fukuchi and Odate 2001, Odate and Fukuchi 2001). Deployment of CPRs on each of these passes enabled the collection of a unique zooplankton data set comprising multiple repeats of the same transect line from a single season. Using these data I aimed to provide the first detailed analysis of the seasonal succession of zooplankton community structure south of Australia. In the light of zonal variation in community structure demonstrated in Chapter 4, the analysis was divided between two major regions:

1. The Seasonal Ice Zone, analysed in Chapter 5
2. The Sub-Antarctic Zone / Inter Sub-Antarctic Front Zone / Polar Frontal Zone, analysed in Chapter 6

5.1.2. The Seasonal Ice Zone

The Antarctic Seasonal Ice Zone (SIZ) comprises an area of approximately 16 million km^2, and represents a region of major ecological significance (Nicol and Allison 1997, Treguer and Jacques 1992). The spring sea-ice melt is associated with enhanced food availability, through the release of sea-ice biota (Heywood and Whitaker 1984), and primary production enhancement associated with the retreating ice-edge (Smith and Sakshaung 1990). The seasonal cycles of zooplankton population growth and development are intimately linked to these cycles of food availability (Hopkins and Torres 1989, Quetin et al. 1996, Loeb et al. 1997, Burghart et al. 1999). With a maximum winter coverage of 20 million km^2 the sea-ice provides a habitat and substrate for micro-organisms (Eicken 1992), and is considered to play an important role as a winter nursery for metazoan plankton and the keystone species *Euphausia superba* (Antarctic krill) (Quetin et al. 1996, Nicol and Allison 1997, Atkinson 1998). The invertebrates supported by the SIZ in turn feed a host of vertebrate predators, many of which utilise the sea-ice as a resting platform and breeding ground (Eicken 1992, Nicol and Allison 1997).

The Antarctic region and SIZ are considered to be particularly susceptible to the effects of global climate change (Zwally 1994, Nicol and Allison 1997). A decrease in average se-ice extent is predicted in response to climate warming

(Zwally 1994, Loeb et al. 1997), and evidence suggests that a substantial reduction in sea-ice has already occurred in the last century (de la Mare 1997). Inter-annual data sets have demonstrated that short term variations in the biomass and relative contribution of the key zooplankton species *Euphausia superba* and *Salpa thompsoni* are intimately linked to sea-ice extent (Loeb et al. 1997). However, few long-term zooplankton data sets exist for the SIZ (El-Sayed 1998). Satellite imagery has shown that there is substantial circumpolar variation in both the extent of the SIZ and its seasonal cycle of growth and retreat (Comiso et al. 1993, Worby et al. 1998). Studies in regions of low sea-ice extent provide an alternative means of gaining insights into the ecological impacts of long-term climate warming (Chiba et al. 2001, Nicol et al. 2000c).

South of Australia, the region between 115°E to 150°E is characterised by a narrow SIZ (Nicol et al. 2000a). Indeed, the sea-ice may extend only 300 km from the coast, equivalent in width to the marginal ice zone in other areas of Antarctica (Worby et al. 1998). Therefore, in addition to identifying the seasonal variation of zooplankton communities, analysis of the SIZ data collected along 140°E during the Australian-Japanese collaborative study provided insights into community dynamics in a region of low sea-ice extent.

5.2. Methods

5.2.1. Data Collection

Between November 2001 and March 2002 six repeats were made of the 140°E SIZ transect. Transects were completed on 22-28 November (Transect A), 10-15 January (Transect B), 11-12 February (Transect C), 19-22 February (Transect D), 25-26 February (Transect E), and 10-11 March (Transect F) (Table 5.1). Details of vessels used for each transect and sample locations are presented in Table 5.1 and Figure 5.1. Zooplankton were collected with a CPR on the January, February and March transects. Based on the low inter-vessel depth variation recorded by Hays and Warner (1993), the sampling depth of the CPR from the RV *Hakuho Maru*, RV *Tangaroa* and RV *Shirase* would have been within a few meters of the ~ 10.5m recorded from the RV *Aurora Australis* (Hunt and Hosie 2003). As no flowmeter was attached to the CPR filtration efficiency was assumed to be 100%.

Table 5.1. Details of zooplankton sampling completed along 140°E between November 2001 and March 2002, including vessels used, net type, sampling period and spatial coverage.

Transect	Ship	Net	Sample period	Latitude	Longitude
A	*Aurora Australis*	NORPAC	22-28 Nov '01	62°S - 66.00°S	140°E
B	*Hakuho Maru*	CPR	10-15 Jan '02	62°S - 65.50°S	140°E
C	*Tangaroa*	CPR	11-12 Feb '02	62°S - 66.24°S	140°E
D	*Tangaroa*	CPR	19-22 Feb '02	62°S - 64.50°S	140°E
E	*Tangaroa*	CPR	25-26 Feb '02	62°S - 66.36°S	140°E
F	*Shirase*	CPR	10-11 Mar '02	62°S - 65.43°S	140°E

The CPR could not be deployed in November as the sea-ice extended to ~ 62.50°S. These samples were therefore collected with a NORPAC net at 10 stations coinciding with CTDs, spaced approximately 30' latitude apart. Due to the thickness of the sea-ice along 140°E the ship (and hence Transect A) diverged to the east. The NORPAC net (45cm diameter) was fitted with the same mesh used in the CPR survey (270μm), and was hauled vertically between 0 and 20m to make these samples comparable with those collected by the CPR. A mechanical revolution counting flowmeter (Rigosha and Co., Ltd, no. 5571-A) was secured across the mouth of the NORPAC net for volume filtered calculation.

The collection, treatment and processing of samples followed the protocol in Section 2.3.2. The entire contents of all Transect E and Transect F samples were identified and enumerated, while the Transect A, B, C, and D samples were sub-sampled using a box splitter, and aliquots ranged between one-half and one-sixteenth of the total. Identification was to species and stage level wherever possible, and followed the protocol in Section 2.3.3. Copepodite stages C1 to C3 of *Calanus propinquus*, *Calanus simillimus* and *Calanoides acutus* were not identified to species, and were grouped together as large calanoid copepodites (C1-3). Gelatinous and other soft bodied plankton are typically damaged during collection by the CPR. To facilitate comparison of samples collected by the two net systems the soft bodied species identified in the NORPAC samples were placed in the same groupings used for the CPR samples i.e. appendicularians, hydromedusae, ctenophores, siphonophores, chaetognaths, *Limacina* spp. and *Tomopteris* spp.. All *Salpa thompsoni* specimens collected were of the aggregate form. The *Euphausia superba* recorded on Transect B were all adult specimens, while those recorded on

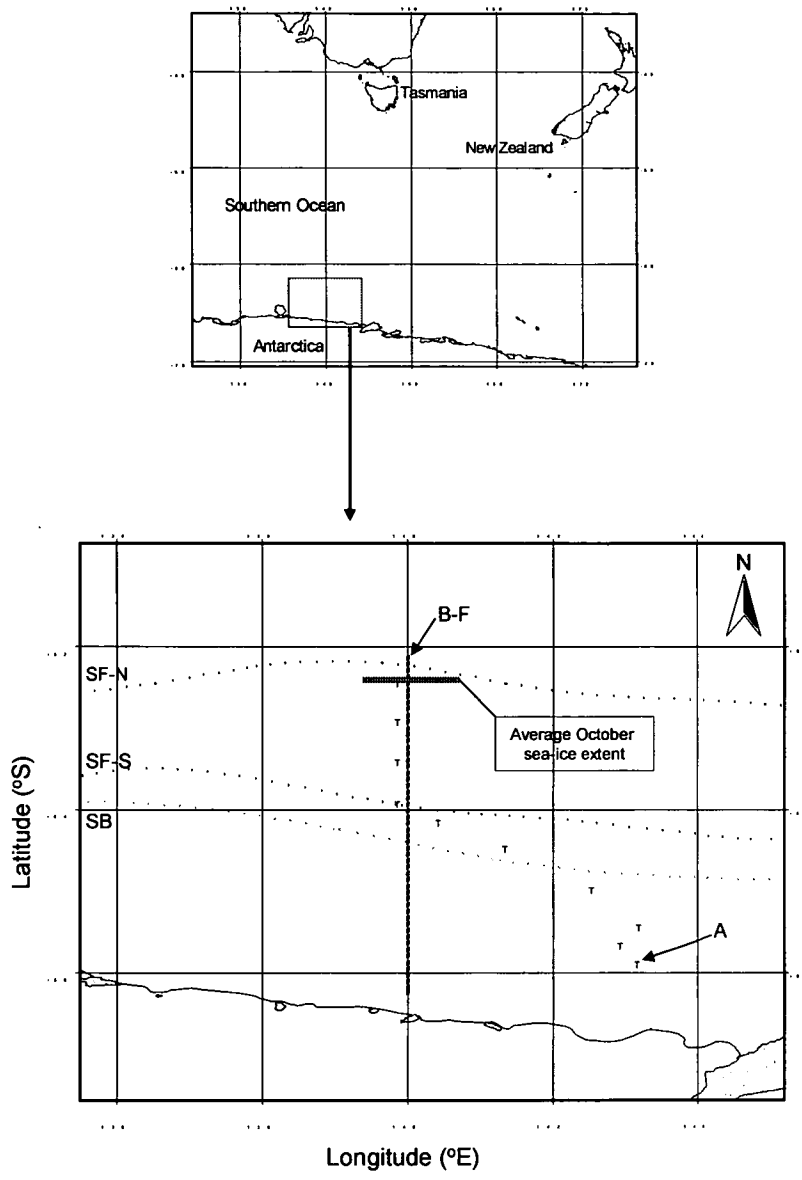


Figure 5.1. Map of the study area, indicating the position of zooplankton transects A (Δ) and B to F (•). Average maximum sea-ice extent along 140°E (62.60°S, recorded in October), and the average locations of the northern and southern braches of the Southern Front (SF-N and SF-S) and the Southern Boundary of the ACC (SB) are indicated. Sea-ice extent was determined using data from the U.S. Navy / NOAA Joint Ice Centre (JIC) (http://www.antcrc.utas.edu.au/~jacka/seaice.html). Frontal positions are those of Sokolov and Rintoul (2002).

subsequent transects were larvae. Zooplankton abundance was converted to individuals.m^{-3}.

Ship board meters were used to take underway measurements of Sea Surface Temperature (SST), Surface Salinity (SS) and Photosynthetically Active Radiation (PAR) at one minute intervals. Sea Surface Temperature was recorded on all six transect, SS on Transects A, B, C and F, and PAR on Transects A, C, D and E. Twenty two CTD casts were made from 19-28 November 2001 (Transect A) using a General Oceanics Mark IIIC CTD. A further nine casts were made from 11-12 February (Transect D) using a SBE 119 CTD. Data from the two CTD transects were used to plot 1000m depth vertical profiles of the water column.

5.2.2. Analysis

A sample by taxon matrix was produced for multivariate analysis from which copepodite stages C1 to C3 and unidentified nauplii were excluded, and the stages of other taxa were merged. As the primary focus of this study was the seasonal succession of SIZ community structure all samples north of 62°S (Appendix 1) were excluded from the analysis. This coincided approximately with the northern branch of the Southern Antarctic Circumpolar Current Front, and concomitantly the winter maximum of the sea ice distribution (Worby et al. 1998, Sokolov and Rintoul 2002). To remove the influence of diel variation, a prominent feature of CPR samples (Hunt and Hosie 2003), the data set was divided into night and day samples. Night was defined as samples where PAR < 100 $\mu mol.s^{-1}.m^{-2}$, or, where PAR was not measured, between sunset and sunrise. The night and day subsets comprised 113 and 122 samples, respectively.

The seasonal succession of zooplankton communities in the night and day data sets was subsequently investigated in terms of **1.** taxonomic composition, **2.** a dissimilarity coefficient, **3.** abundance levels, and **4.** the proportional contribution of taxa. This was done through the application of two multivariate techniques, Cluster Analysis and Correspondence Analysis.

5.2.2.1. Taxonomic composition

The complete taxonomic list was reduced to a presence / absence matrix. Sorensen's coefficient was applied to produce a dissimilarity matrix before cluster

analysis using Un-Weighted Pair Group Average (UMPGA) linkage (Legendre and Legendre 1998). Presence / Absence analysis weighted rare and abundant taxa equally and gave insight into seasonal changes in the taxonomic composition of communities. The Information Statistic (2ΔI) was used to identify the species primarily responsible for sample clusters (Field et al. 1982):

$$2\Delta I_i = 2(I_{ti} - I_{1t} - I_{2t})$$

where I_{ti} is the total information content of two clusters combined:

$$I_{ti} = N_t \log N_t - A_{ti} \log A_{ti} - (N_t - A_{ti}) \log (N_t - A_{ti})$$

N_t = number of samples in both clusters together; A_{ti} = number of samples in which species *i* is actually present; $(N_t - A_{ti})$ = number of samples from which species *i* is absent. Similarly, the information content of the two clusters being compared was calculated (I_{1t} and I_{2t}). As $2\Delta I_i$ has an approximate chi-square distribution, indicator species were selected based on the 1% and 5% probability levels, corresponding with $2\Delta I_i > 6.635$ and $2\Delta I_i > 3.841$, respectively (Field et al. 1982). The information statistic was calculated in a pair-wise fashion for cluster groupings at each level of separation.

5.2.2.2. Dissimilarity Coefficient

A second Cluster Analysis was performed on the full species set, after $\log_{10}(x+1)$ transformation of abundance levels, using the Bray-Curtis dissimilarity coefficient and UMPGA linkage (following the protocol in section 3.2.2.2). The Bray-Curtis dissimilarity coefficient had the effect of emphasising dominant taxa yet still considering numerically minor species (Field et al. 1982), and was therefore intermediate between analysis of Taxonomic Composition (section 5.2.2.1) and Taxon Abundance Levels (section 5.2.2.3). Dufrene and Legendre's (1997) indicator value (IndVal) analysis was applied to sample groupings at each level of separation in the cluster analysis, following the protocol in section 4.2.2. The IndVal method combined measures of group specificity (A_{ij}) and group fidelity (B_{ij}) and was thus complementary to the Bray-Curtis dissimilarity coefficient. Indicator values of ≥

25% were used, which meant that a taxon was present in at least 50% of samples in a group and that its relative abundance in that group was at least 50%.

5.2.2.3. Abundance levels

A third cluster analysis was performed on the raw abundance data (individuals.m^{-3}) using the Manhattan Metric and UMPGA linkage. The Manhattan Metric (MM) calculated the distance between two samples as the sum of the differences in species abundance levels for the two sampling units being compared (Pielou 1984):

$$MM = \sum_{i=1}^{s} |x_{ij} - x_{i2}|$$

$|x_{i1} - x_{i2}|$ denotes the absolute magnitude of the difference in abundance of species i in samples 1 and 2, and is taken as positive no matter what the sign of $(x_{i1}-x_{i2})$. Double zeros lead to a reduction in distance between samples and consequently this analysis was performed on a data set reduced to taxa occurring in $\geq$ 20 % of samples (Legendre and Legendre 1998). As absolute abundance values were used the Manhattan Metric focused attention on seasonal changes in the abundance levels of dominant taxa. Differences in the abundance levels of taxa between clusters were investigated by ANOVA of $\log_{10}(x+1)$ transformed abundance data. Where significant differences in abundance were detected Newman-Keuls multiple range tests were performed to identify inter-cluster differences.

5.2.2.4. Proportional Composition

The proportional contribution of taxa to community structure was investigated using Correspondence Analysis. In Correspondence Analysis the relationship between samples / rows is quantified using the X^2 distance, and consequently the resulting ordinations are a reflection of the proportional contribution of taxa to total abundance (Ortner et al. 1989). Analysis was performed on the data set reduced to species occurring in $\geq$ 20% of samples across the survey in order to focus attention on the dominant taxa. The Correspondence Analysis was therefore complementary to the Manhattan Metric (Section 5.2.2.4).

5.3. Results

5.3.1. Physical Environment

The region south of 60°S is bisected by four fronts, including two branches (northern and southern) of the Southern Front (SF), the Southern Boundary (SB) of the eastward flowing Antarctic Circumpolar Current (ACC), and the Antarctic Slope Front (ASF), located within the westward flowing Coastal Current (CC) on the continental shelf break (Section 2.2.2). Based on the frontal definitions in Table 2.1 the northern branch of the SF was located at ~ 62.25°S (Figure 5.2a), and the southern branch of the SF at ~ 64.40°S (Figure 5.2b). The latitudes of both branches of the SF were very similar on the 11-12 February (Figure 4.3), and inter-annual observations have shown that they vary by < 0.5° about their mean latitude (Sokolov and Rintoul 2002).

The SB was defined by the southern limit of water warmer than 1.5°C, the temperature maximum layer, placing it at ~ 64.50°S on the 22-28 November section (Figure 5.2a), and ~ 64.70°S on the 11-12 February section, well within its normal range. The close proximity of the SB and SF-S is characteristic along 140°E and on previous occasions they have appeared to be merged (Sokolov and Rintoul 2002). Given the close proximity of the SF-S and the SB, and the weak surface expression of the former, attention has been focused on the SB in this study. The ASF is characterised by a deepening of temperature and salinity isotherms and isohalines respectively towards the south, and accordingly the ASF was located at ~ 65.25°S on both transects (Figure 5.2a).

The SST profile on Transect A was characterised by values < -1.0°C south of ~ 62.50°S, coinciding with the northern edge of the sea ice (visual observations) (Figure 5.3). By Transect B, SST had warmed by approximately 2.0°C across the length of the transect. SST warmed still further by Transect C, with the coolest water (~ 0.25°C) occurring south of the ASF. From Transect C onwards SST remained comparatively warm to the north of the SB, ranging between 1.5°C and 3.5°C, and dropped off sharply to the south of this front, in the CC. On all transects where SS was measured values ranged between 33.10 and 33.85 north of the SB, and increased rapidly to the south of this front, in the CC. These SS data demonstrated that on Transects A and B, where SST was still undergoing summer warming, that the position of the SB was at ~ 64.50°S. Data from Transect C concurred with the

vertical profile for 11-12 February, indicating that the SB was slightly further south, between 64.70 and 65.00°S. On the remaining transects D, E and F, the SB had a relatively constant position of ~ 64.50°S.

5.3.2. Zooplankton Community Structure

5.3.2.1. Night Communities

Presence / Absence analysis identified five sample clusters (Figure 5.4a). Cluster 5 separated at 43.45% dissimilarity and was dominated by Transect F samples north of 62.43°S, but included two segments at 64.42°S and 65.01°S, from Transects D and F respectively. *Clio pyramidata* and *Calanus simillimus* were important indicator species (Table 5.2). *Calanoides acutus*, *Thysanoessa macrura*, *Phalacrophorus pictus*, *Oncaea* spp., *Rhincalanus gigas* and *Euphausia superba* were largely absent from Cluster 5, but occurred at high frequency in Cluster 1 to 4. Cluster 4 comprised all of the Transect A samples, one Transect C and two Transect E samples, and was characterised by the presence of *Stephos longipes* and a high frequency of soft bodied taxa including hydromedusae, siphonophores and *Tomopteris* spp.. Clusters 1, 2 and 3 had a relatively low dissimilarity (< 33%) and together they were characterised by a high frequency of occurrence of *Limacina* spp.. Cluster 3 comprised the Transect D samples between 62°S and ~ 63°S, the middle samples (63.67°S to 64.74°S) of Transect E, and Transect F samples between 63.94°S and 64.93°S. *Calanus propinquus*, *Metridia gerlachei*, *E. superba*, *Salpa thompsoni* and *Themisto gaudichaudii* were indicator species. Clusters 1 and 2 had a high frequency of occurrence of *R. gigas*, *Oncaea* spp., foraminiferans and *P. pictus*. Cluster 1 included the southernmost samples of Transects B and E, and the latter were located south of the SB. *Euphausia superba* occurred in 9 / 10 samples, and *Microcalanus pygmaeus* was also an indicator. Cluster 2 comprised the majority of Transect B and C samples and differed from Cluster 1 in that it had a high frequency of *C. laticeps* and *C. acutus*.

Using the Bray-Curtis dissimilarity measure four sample clusters were identified, and overall they were similar to those identified by the Presence / Absence analysis (Figure 5.4b). Two samples from Transect A grouped independently of each other and all other samples. These two outliers were not

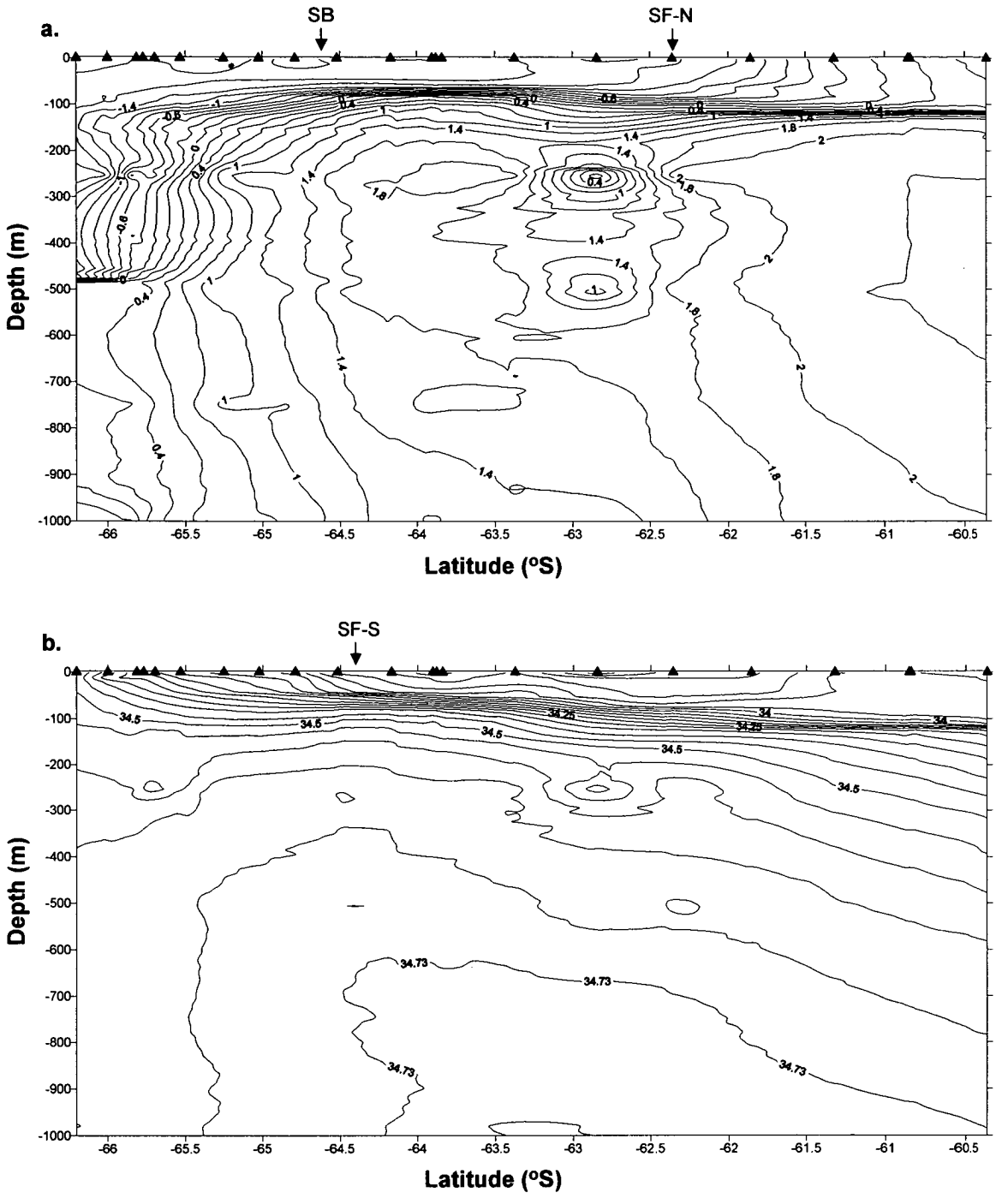


Figure 5.2. Vertical **a.** temperature and **b.** salinity profiles through the upper 1000m of the water column determined from twenty two CTD casts (▲) made from 19-28 November 2001. The northern and southern braches of the Southern Front (SF-N and SF-S) and the Southern Boundary (SB) are indicated.

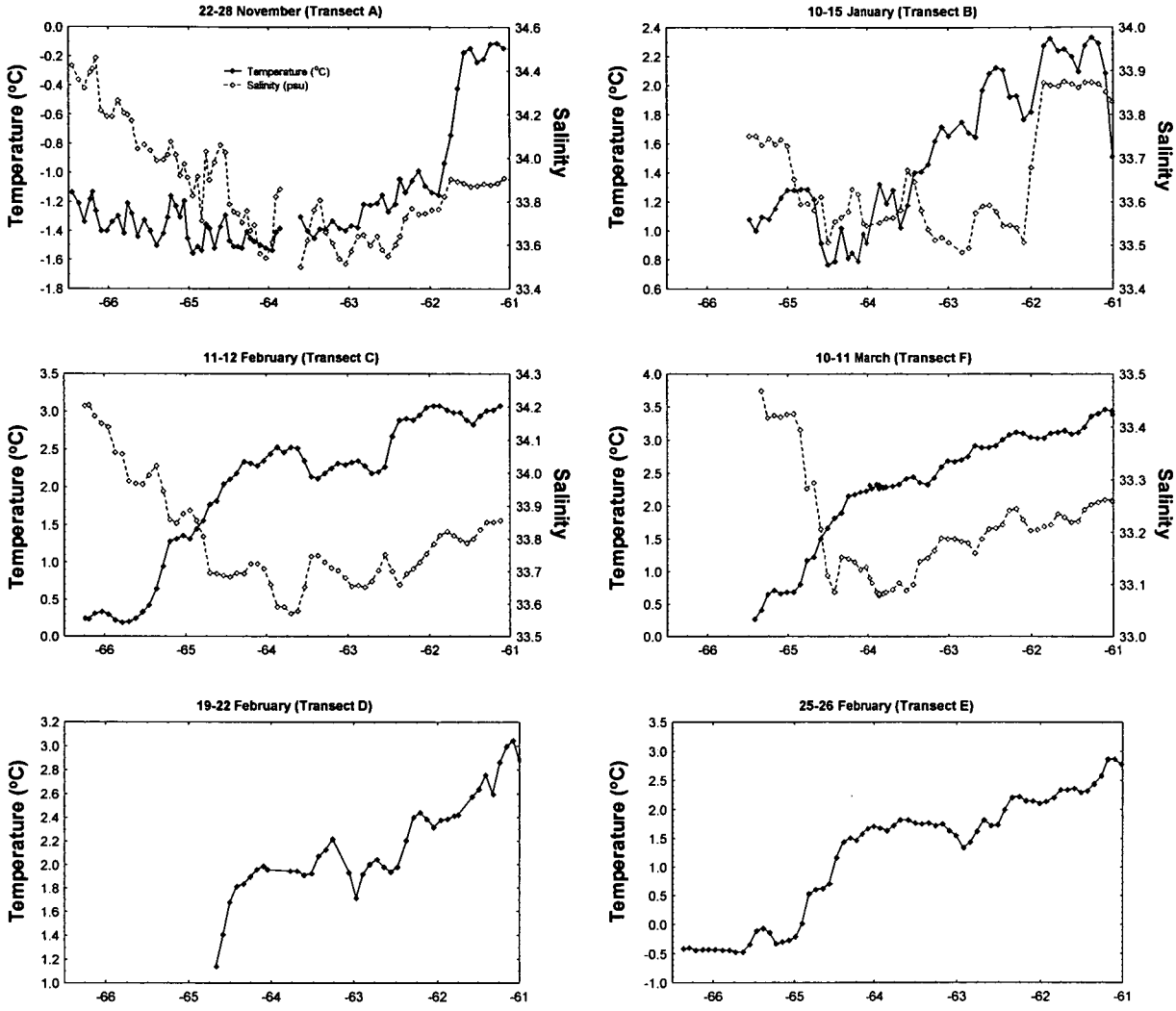


Figure 5.3. Sea Surface Temperature (°C) and Surface Salinity profiles from the six zooplankton transects (A to F) completed between November 2001 and March 2002.

illustrated on Figure 5.4b and were excluded from the IndVal analysis. Cluster 4 separated from Clusters 1 to 3 at 54% dissimilarity, and was equivalent to Cluster 5 of the Presence / Absence analysis. *Clio pyramidata*, *Calanus simillimus* and *Vibilia* sp. had maximum IndVals in Cluster 4 and *S. thompsoni* had a relatively high IndVal (Figure 5.5). The remaining samples (Cluster 1 to 3) had maximum IndVals for appendicularians, *C. citer*, *C. acutus* and *T. macrura*, while values for foraminiferans, *O. similis*, *Limacina* spp., and *R. gigas* exceeded 70%. These taxa therefore formed the basis of the community in most samples. Cluster 3 was similar to Cluster 3 of the Presence / Absence analysis but did not include Transect E samples, reflecting differences in the abundance levels of high frequency taxa. *Calanus propinquus*, *M. gerlachei* and *S. thompsoni* had maximum IndVals while *E. superba* had IndVals exceeding 70%. Together Clusters 1 and 2 had maximum IndVals for foraminiferans, harpacticoids, *Oncaea* spp., and *R. gigas*. Cluster 2 included all samples from Transects B and C, the southern samples of Transect D and the middle samples (63.51°S to 64.42°S) of Transect E. Although *Limacina* spp., *C. laticeps*, and *O. similis* were widespread taxa they had maximum IndVals in Cluster 2, indicating that this was where they had there highest densities. Cluster 1 comprised two Transect A samples and the Transect E samples south of 64.42°S, and *E. superba* was an important indicator species although being absent from the two Transect A samples.

Reduction of the data set to taxa occurring in ≥ 20% of samples left 17 taxa in the night analysis (Table 5.3). Four sample clusters were identified using the Manhattan Metric (Figure 5.4c). Cluster 1 comprised all Transect A samples, and progressively more samples moving from Transect B to Transect F. Cluster 1 was characterised by low abundance of most taxa, although *C. propinquus*, *M. gerlachei*, and *S. thompsoni* had relatively high abundance levels, and *E. superba* was significantly more abundant than in any other cluster (Table 5.3). Cluster 2 comprised the three northernmost Transect B samples, Transect C samples (predominantly between 62.5°S and 63.5°S), and the majority of Transect E samples between 63.5°S and 64.5°S. Cluster 3 and 4 comprised small groups of Transect C and B samples respectively. *Oithona similis*, *Oncaea* spp., *P. pictus*, *R. gigas*, *T. macrura* and appendicularians all occurred at significantly higher abundance levels in Cluster 4. Cluster 3 was characterised by significantly higher abundance levels of *Limacina* spp. and *C. acutus*. *Limacina* spp. was also an important component of Cluster 2. Abundance levels of foraminiferans, *C. citer* and *C. laticeps* were high

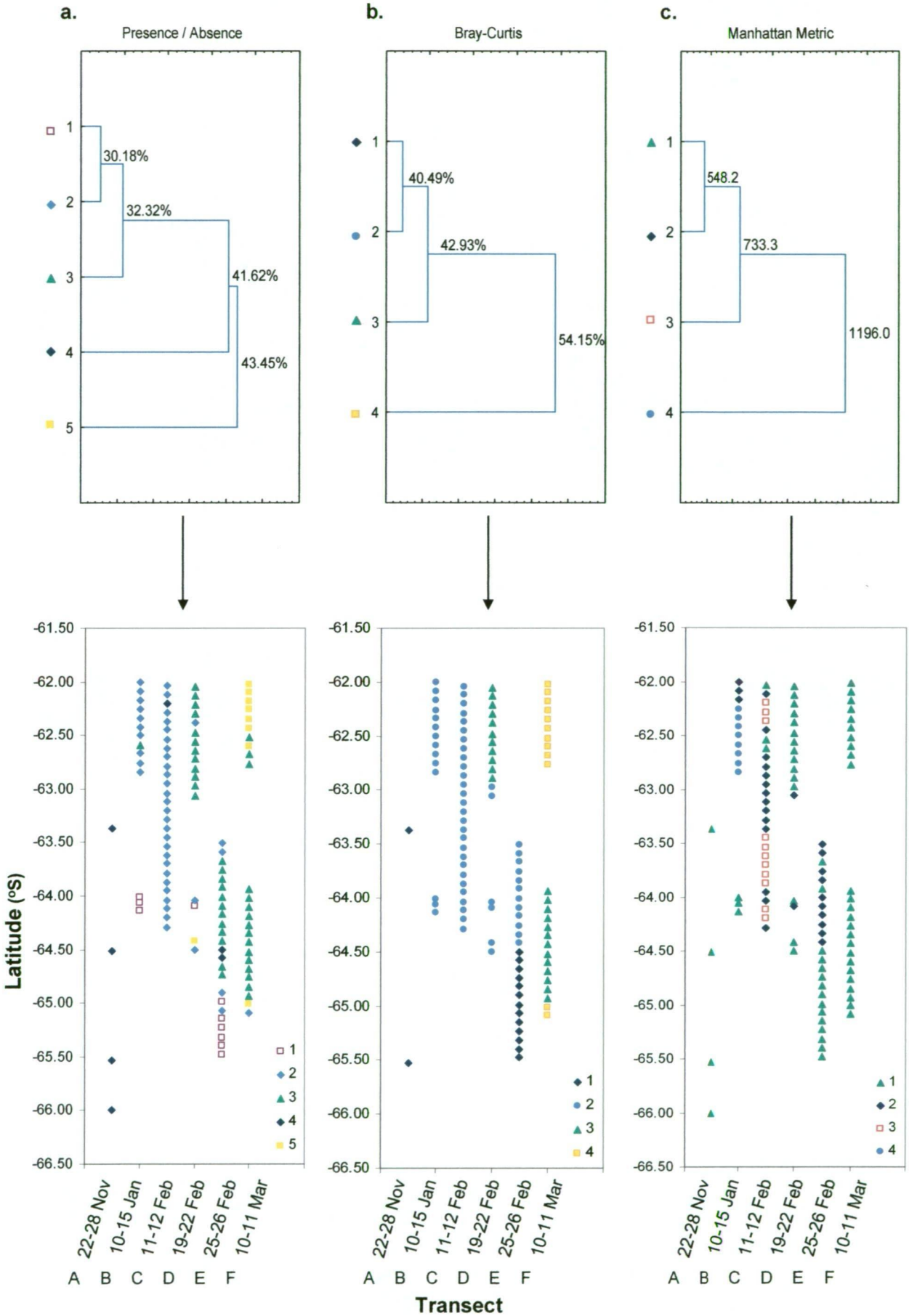


Figure 5.4. *legend overleaf...*

Figure 5.4. Sample groupings from cluster analysis by Un-Weighted Pair Group Average linkage of **night** data, using **a.** Presence / Absence data and Sorenson's Coefficient **b.** $\log_{10}(x+1)$ abundance data and the Bray-Curtis dissimilarity measure **c.** raw abundance data (individuals.m^{-3}) for taxa occurring in $\geq$ 20% of samples and the Manhattan Metric. The upper panel indicates the clusters identified and their level of separation, and the lower panel indicates the spatial and temporal distribution of samples comprising each cluster.

Table 5.2. Frequency of occurrence of indicator taxa in cluster pairs determined by Presence / Absence analysis of **night** samples (Figure 5.4a). Indicator taxa (in **bold**) were identified by the Information Statistic - 2ΔI (Field et al. 1982). As 2ΔI has an approximate chi-square distribution indicator species were selected based on the 1% and 5% probability levels, corresponding with $2\Delta I_i > 6.635$ and $2\Delta I_i > 3.841$ respectively. Taxa above the space had $2\Delta I > 6.63$ and taxa below the space had $2\Delta I > 3.84$.

	Cluster 5 (n=9)	Cluster 1 to 4 (n=103)		Cluster 4 (n=7)	Cluster 1 to 3 (n=96)
Clio pyramidata	**6**	3	*Limacina* spp.	2	**91**
Calanoides acutus	0	**83**			
Thysanoessa macrura	1	**83**	*Clausocalanus laticeps*	2	**80**
			Hydromedusa	**3**	1
Calanus simillimus	**6**	11	Siphonophore	**2**	1
Phalacrophorus pictus	0	**51**	*Tomopteris* spp.	**3**	1
Oncaea spp.	0	**59**	*Stephos longipes*	**2**	0
Rhincalanus gigas	1	**71**			
Euphausia superba	0	**48**			

	Cluster 3 (n=41)	Cluster 1 and 2 (n=55)		Cluster 1 (n=10)	Cluster 2 (n=45)
Calanus propinquus	**38**	4	*Clausocalanus laticeps*	0	**41**
Metridia gerlachei	**26**	6	*Euphausia superba*	**9**	5
Euphausia superba	**32**	14			
Salpa thompsoni	**38**	17			
Rhincalanus gigas	18	**50**	*Thysanoessa macrura*	4	**39**
			Calanoides acutus	3	**39**
Themisto gaudichaudii	**10**	2	*Microcalanus pygmaeus*	**5**	2
Oncaea spp.	15	**40**			
Foraminifera	34	**55**			
Phalacrophorus pictus	12	**35**			

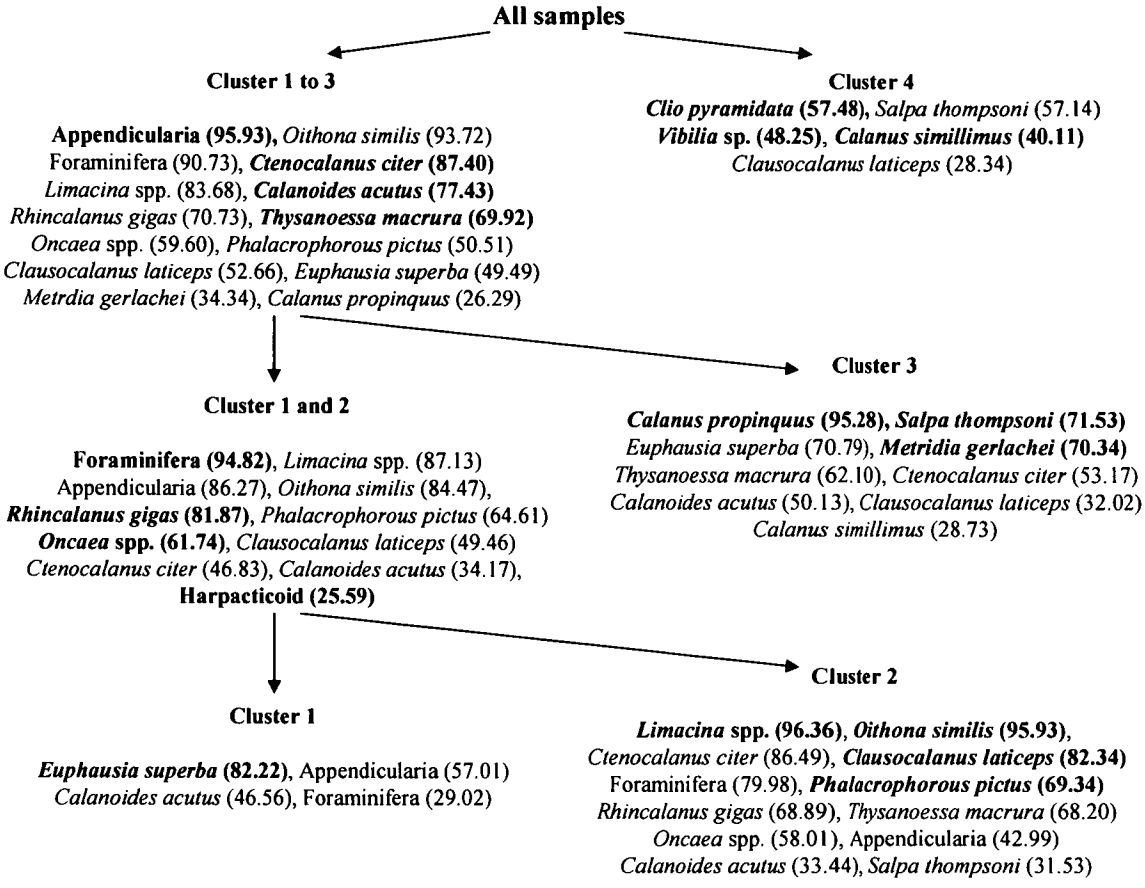


Figure 5.5. Night indicator taxa identified by applying Dufrene and Legendre's (1997) technique to clusters obtained using the Bray-Curtis dissimilarity measure and Un-Weighted Pair Group Average linkage. Taxa indicated for each sample grouping had indicator values ≥ 25%, which meant that they were present in at least 50% of samples in a group and that their relative abundance in that group was at least 50%. Maximum Indicator Values are in bold.

Table 5.3. Average abundance (individuals.m^{-3}) of zooplankton taxa occurring in ≥ 20% of **night** samples, for the four clusters identified using the Manhattan Metric (Figure 5.4c). Differences between clusters were investigated using ANOVA, performed on $\log_{10}(x+1)$ transformed abundance levels. Significance levels are indicated by F and p. Newman-Keuls multiple range tests were performed to identify inter-cluster differences in species abundance levels. Significantly higher abundance levels are in bold and underlined. ** $p < 0.001$, *** $p < 0.0001$.

Taxon	Cluster 1 (n=65)	Cluster 2 (n=29)	Cluster 3 (n=11)	Cluster 4 (n=8)	F	p
Foraminifera	18.43	**57.49**	**68.48**	**63.44**	29.63	***
Phalacrophorus pictus	0.24	2.39	4.50	**6.78**	33.97	***
***Limacina* spp.**	15.63	147.92	**349.08**	8.70	53.68	***
Calanoides acutus	2.45	2.83	4.06	1.41		
Calanus propinquus	3.48	0.64	0.12	0.17		
Clausocalanus laticeps	1.77	**5.22**	**5.79**	**6.97**	17.85	***
Ctenocalanus citer	32.11	**57.91**	**72.22**	**125.02**	14.03	***
Harpacticoid	0.17	0.55	0.97	0.98		
Metridia gerlachei	1.04	0.30	0.48	0.34		
Oithona similis	51.41	311.65	480.69	**855.79**	83.69	***
***Oncaea* spp.**	0.81	3.05	5.42	**9.22**	13.23	***
Rhincalanus gigas	0.87	4.67	3.36	**21.61**	49.54	***
Euphausia superba	**18.44**	2.46	0.00	0.00	6.38	**
Thysanoessa macrura	2.30	1.93	1.40	**6.19**	5.87	**
Chaetognatha	0.18	0.46	0.79	0.00		
Salpa thompsoni	0.99	0.73	0.19	0.75		
Appendicularia	64.64	108.73	111.94	**305.65**	19.12	***

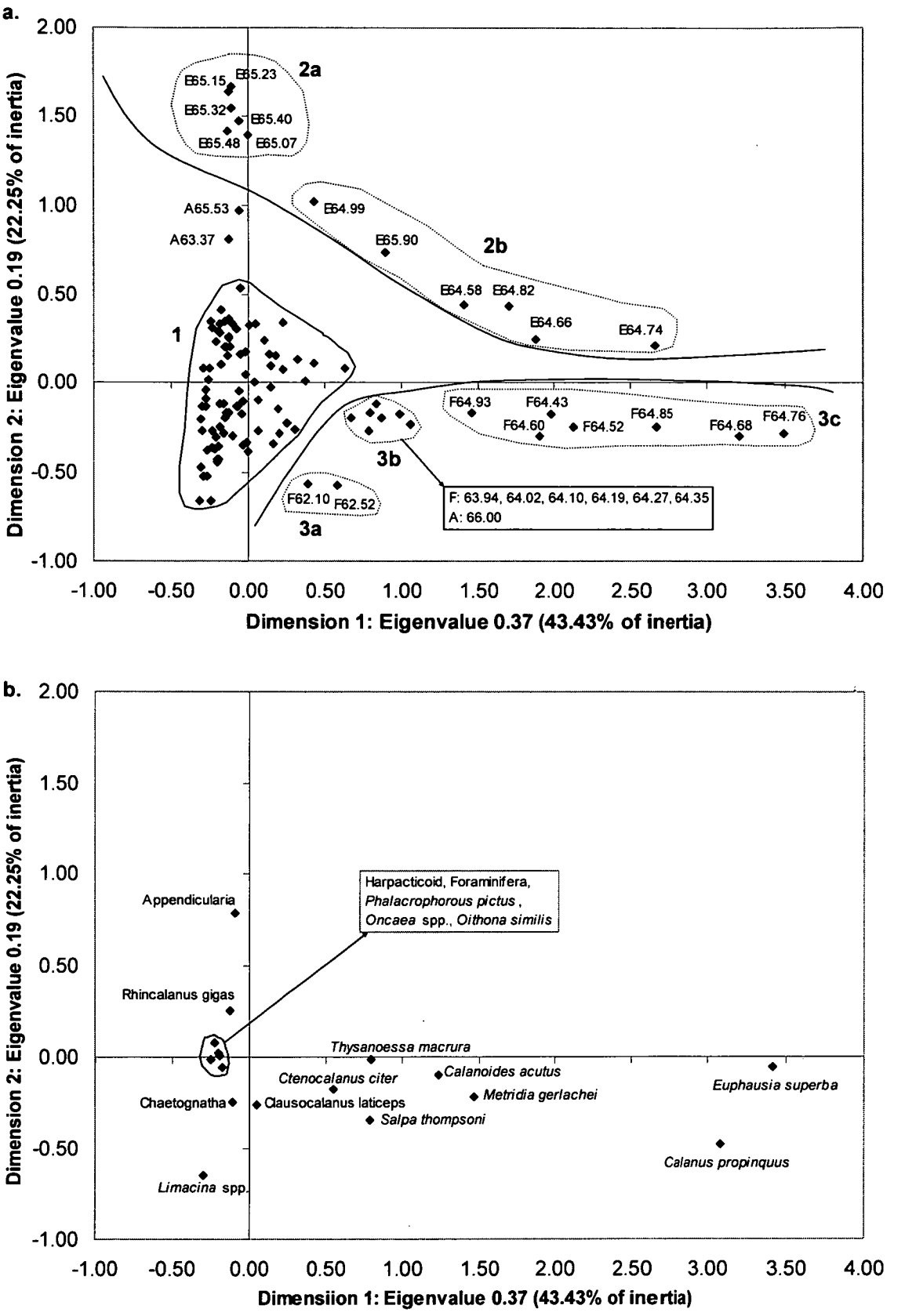


Figure 5.6. Ordination of **a.** samples and **b.** taxa using the first two dimensions of the Correspondence Analysis, based on taxa occurring in ≥ 20% of **night** samples.

and not significantly different between Clusters 2, 3 and 4, while *Oithona similis* was the most abundant taxon in these clusters.

The percentage contribution of taxa to community structure demonstrated a high degree of similarity between samples with 83 / 113 samples being closely clustered in Group 1 (Figure 5.6a). Group 1 was characterised by the relatively high percentage contribution to abundance made by *O. similis*, *Oncaea* spp., *R. gigas*, foraminiferans, harpacticoids, chaetognaths, *Limacina* spp. *P. pictus* and *C. laticeps* (Figure 5.6b). The distribution of Group 1 samples along the y-axis demonstrated a gradation from a comparatively high contribution of *Limacina* spp. on the negative side, to appendicularians on the positive side, around the core taxa. The samples located outside of Group 1 were predominantly from Transect E and F. Group 2a, comprising Transect E samples south of 65°S, was characterised by a higher than average proportion of appendicularians. Group 2b samples reflected an increasing contribution of taxa distributed towards the positive end of the x-axis, including *C. acutus*, *M. gerlachei*, *C. propinquus* and *E. superba*. Group 3a comprised two samples from the north of Transect F and appeared to be influenced by a high contribution of *S. thompsoni*, *C. laticeps* and *Limacina spp.*. Groups 3b and 3c predominantly comprised Transect F samples between 64°S and 65°S. Group 3b included the more northerly of these segments and one Transect A sample, and had a high contribution of *T. macrura*, *C. citer*, *C. laticeps*, *S. thompsoni*, *C. acutus*, and *M. gerlachei*. Group 3c included the more southerly Transect F samples and, similar to the 2b samples, was characterised by a high proportional contribution of *C. acutus*, *M. gerlachei*, *C. propinquus* and *E. superba*. Within Group 3c a gradation was evident in the along the x-axis, in the positive direction, from samples with a high proportion of *C. acutus* and *M. gerlachei* to samples with a high proportion of *C. propinquus* and *E. superba*. Two Transect A samples were located between Groups 1 and 2.

5.3.2.2. Day Communities

Five sample clusters were identified from the Presence / Absence analysis of day samples (Figure 5.7a). Sixteen samples grouped individually or in pairs, indicating a higher degree of heterogeneity in species composition than in the night samples. These sixteen samples were not illustrated on Figure 5.7a, and were excluded from the subsequent Information Statistic analysis (2ΔI). Cluster 5 and 4

both comprised Transect F samples, and predominantly those between 63°S and 64°S. One Cluster 5 sample was located south of the SB. Cluster 5 was characterised by the absence or low frequency of occurrence of appendicularians, foraminiferans, *C. citer* and *O. similis* (Table 5.4). Cluster 4 samples were characterised by the high frequency of *C. simillimus*, *C. propinquus*, *C. laticeps*, *Vibilia* spp., *T. macrura*, *S. thompsoni* and *M. gerlachei*, a low frequency of *Oncaea* spp., and the absence of foraminiferans and appendicularians. The separation of Clusters 4 and 5 occurred despite their spatial overlap, indicating day-time patchiness in this region. Together, the samples from Clusters 1 to 3 had a high frequency of occurrence of foraminiferans and appendicularians. As in the night analysis the Transect A samples grouped separately (Cluster 3) and *Spongiobranchea australis*, *C. acutus*, *S. longipes*, chaetognaths, *P. pictus* and *T. macrura* were indicator species. Clusters 1 and 2 had a relatively low dissimilarity (~ 33%). Cluster 2 included the majority of segments from Transect B, C, D and E, as well as six segments from Transect F. Cluster 1 predominantly comprised Transect B samples south of 64.5°S and separated from Cluster 2 due to a high frequency of *Calanoides acutus*, *S. longipes, E. superba*, *Primno macropa* and *Oncaea* spp.. The large number of samples in Clusters 2 (75 / 122) indicated that overall there was greater homogeneity in species composition during the day than at night.

Cluster analysis of the Bray-Curtis dissimilarity matrix identified six sample clusters from the day samples (Figure 5.7b). Two outlier samples were identified which were not illustrated on Figure 5.7b, and were excluded from the IndVal analysis. Cluster 6 separated from Cluster 1 to 5 samples at ~ 66% dissimilarity. Cluster 6 comprised the majority of Transect F samples and only *Limacina* spp. and *T. macrura* had IndVals > 25% (Figure 5.8). Clusters 1 to 5 had maximum IndVals for appendicularians and IndVals of > 70% for foraminiferans, *C. citer* and *O. similis*, highlighting the importance of these four taxa in all samples outside of Cluster 6. Cluster 5 separated from Clusters 1 to 4 samples at ~ 56% dissimilarity and comprised Transect E samples between 65.73°S and 66.35°S, and the two southern most samples of Transect F. Cluster 5 was characterised by a lack of IndVal indicator taxa, indicating a low frequency of occurrence and abundance of all taxa. Clusters 1 to 4 had maximum IndVal for *O. similis*. Cluster 4 was similar to Cluster 4 of the Presence / Absence analysis and had maximum IndVals for *C. propinquus*, *C. simillimus*, *C. laticeps, M. gerlachei, Vibilia sp., E. superba* and *S. thompsoni*, while Cluster 1 to 3 samples had maximum IndVal for foraminiferans.

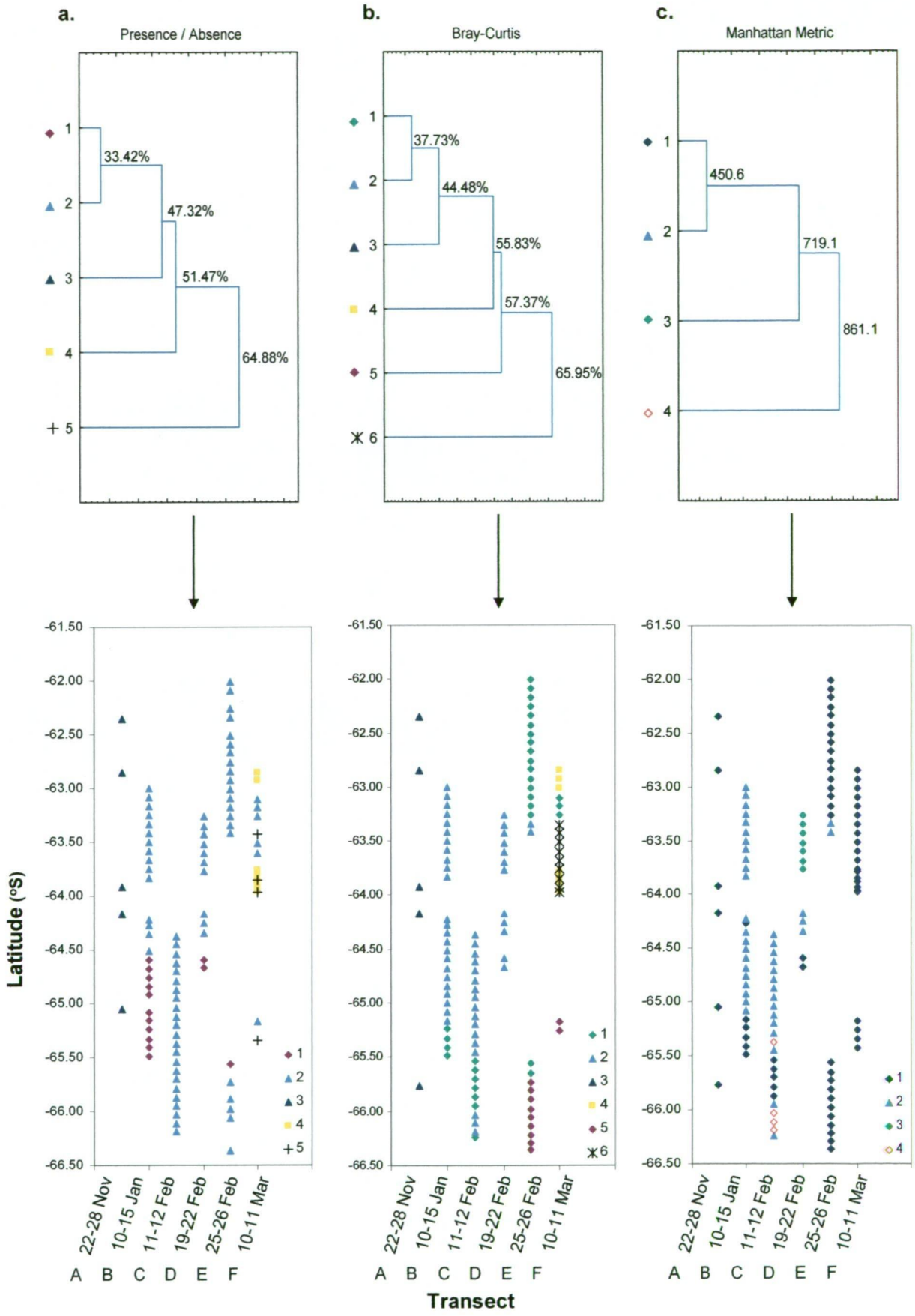


Figure 5.7. *Legend overleaf...*

Figure 5.7. Sample groupings from cluster analysis by Un-Weighted Pair Group Average linkage of **day** samples, using **a.** Presence / Absence data and Sorenson's Coefficient **b.** $\log_{10}(x+1)$ abundance data and the Bray-Curtis dissimilarity measure **c.** raw abundance data (individuals.m^{-3}) for taxa occurring in $\geq$ 20% of samples and the Manhattan Metric. The upper panel indicates the clusters identified and their level of separation, and the lower panel indicates the spatial and temporal distribution of samples comprising each cluster.

Table 5.4. Frequency of occurrence of indicator taxa in cluster pairs determined by Presence / Absence analysis of **day** samples (Figure 5.7a). Indicator taxa (in **bold**) were identified by the Information Statistic - 2ΔI (Field et al. 1982). As 2ΔI has an approximate chi-square distribution indicator species were selected based on the 1% and 5% probability levels, corresponding with $2\Delta I_i > 6.635$ and $2\Delta I_i > 3.841$ respectively. Taxa above the space had $2\Delta I > 6.63$ and taxa below the space had $2\Delta I > 3.84$.

	Cluster 5 (n=4)	**Cluster 1 to 4 (n=102)**		**Cluster 3 (n=5)**	**Cluster 1 and 2 (n=89)**
Appendicularia	0	**99**	*Spongiobranchea australis*	**4**	0
			Calanoides acutus	**5**	10
Foraminifera	1	**98**	*Stephos longipes*	**5**	8
Ctenocalanus citer	0	**81**	Chaetognatha	**4**	4
Oithona similis	2	**101**			
			Phalacrophorus pictus	**5**	18
			Thysanoessa macrura	**4**	14
	Cluster 4 (n=8)	**Cluster 1 to 3 (n=94)**		**Cluster 1 (n=14)**	**Cluster 2 (n=75)**
Foraminifera	4	**94**	*Calanoides acutus*	**7**	3
Appendicularia	5	**94**	*Stephos longipes*	**7**	1
Calanus propinquus	**7**	8	*Euphausia superba*	**11**	2
Calanus simillimus	**6**	9			
Clausocalanus laticeps	**8**	29	*Primno macropa*	**3**	0
Vibilia sp.	**5**	0	*Oncaea* spp.	**14**	43
Thysanoessa macrura	**7**	18	*Calanus simillimus*	**5**	3
Salpa thompsoni	**6**	2			
Oncaea spp.	**0**	59			
Metridia lucens	**2**	0			

Cluster 3, comprising five Transect A samples, separated from Cluster 1 and 2 at ~ 44% dissimilarity and had six taxa with maximum IndVals, including *P. pictus*, *S. australis*, *C. acutus*, *S. longipes*, chaetognaths and *T. macrura*. Together, Cluster 1 and 2 samples had maximum IndVal for *Limacina* spp.. Cluster 2 included the majority of Transect B, C and D samples, and two samples from Transect E, and had maximum IndVals for *C. citer*, *Oncaea* spp. and *R. gigas*. Cluster 1 comprised the majority of samples from Transect E, as well as samples from Transects B, C and F, and had no indicator taxa.

Reduction of the data set to taxa occurring in ≥ 20% of samples left 10 taxa in the day analysis (Table 5.5). *Calanus propinquus*, *C. simillimus*, *C. acutus*, *M. gerlachei*, *E. superba*, chaetognaths and *S. thompsoni* all occurred at low frequencies during the day and were absent from this species sub-set. Four sample clusters were identified using the Manhattan Metric (Figure 5.7c). Cluster 1 comprised all Transect A samples, and an increasing proportion of samples moving from Transect B to F. Cluster 2 was dominated by Transect B and C samples. Cluster 3 comprised seven Transect D samples from between 63.26°S and 63.77°S, while Cluster 4 comprised four southerly Transect C samples from between 65.37°S and 66.19°S. All taxa occurred at low levels of abundance in Cluster 1. Cluster 3 had significantly higher abundance levels of *C. laticeps* and *O. similis*, while *C. citer* was an important component of both Clusters 2 and 3. Cluster 4 had the highest densities of *R. gigas* and appendicularians, the latter exceeding levels in the night data set. Foraminiferans, *Limacina* spp., and *Oncaea* spp. all occurred at significantly higher abundance levels in Cluster 2, 3 and 4 than in Cluster 1.

As in the night samples, a high degree of similarity was evident in community structure based on the percentage contribution of taxa to samples (Figure 5.9). Seventy-eight of 122 samples fell within Group 2 and the majority of the remaining samples were from Transects C, E and F (Figure 5.9a). Group 1 was dominated by Transect C and E samples south of 65.5°S and appendicularians were the most important community component (Figure 5.9b). Group 2 samples were characterised by a high contribution to abundance by *O. similis*, foraminiferans, *R. gigas*, and *Oncaea* spp.. The gradation of these taxa along the x-axis indicated that the proportional contribution did vary within Group 2, however, within group differences were small in comparison to between group differences. Group 3 comprised Transect E and F samples north of 63°S and had a high proportion of *Limacina* spp. and *C. citer*. Group 4 largely comprised Transect F samples from

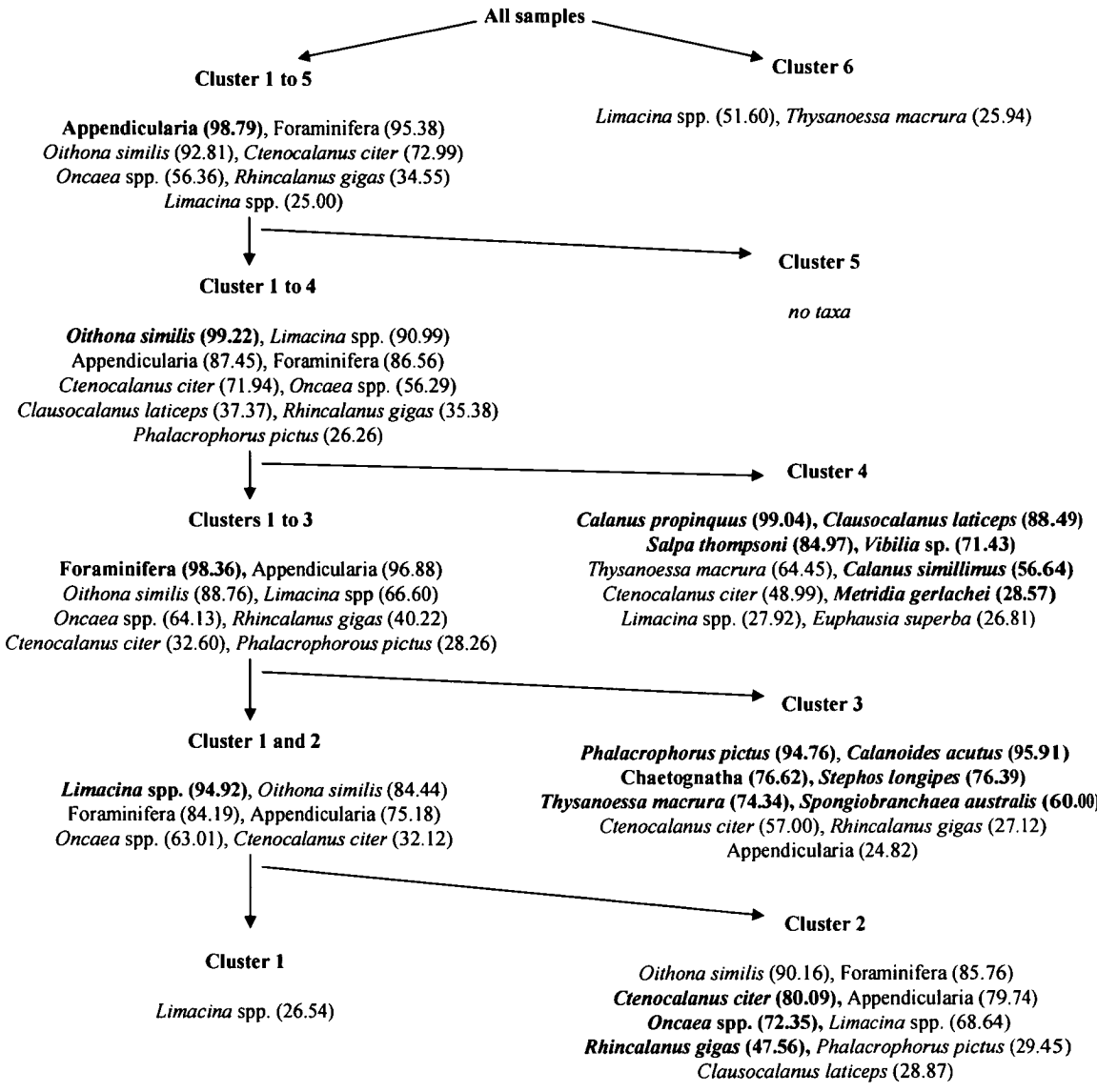
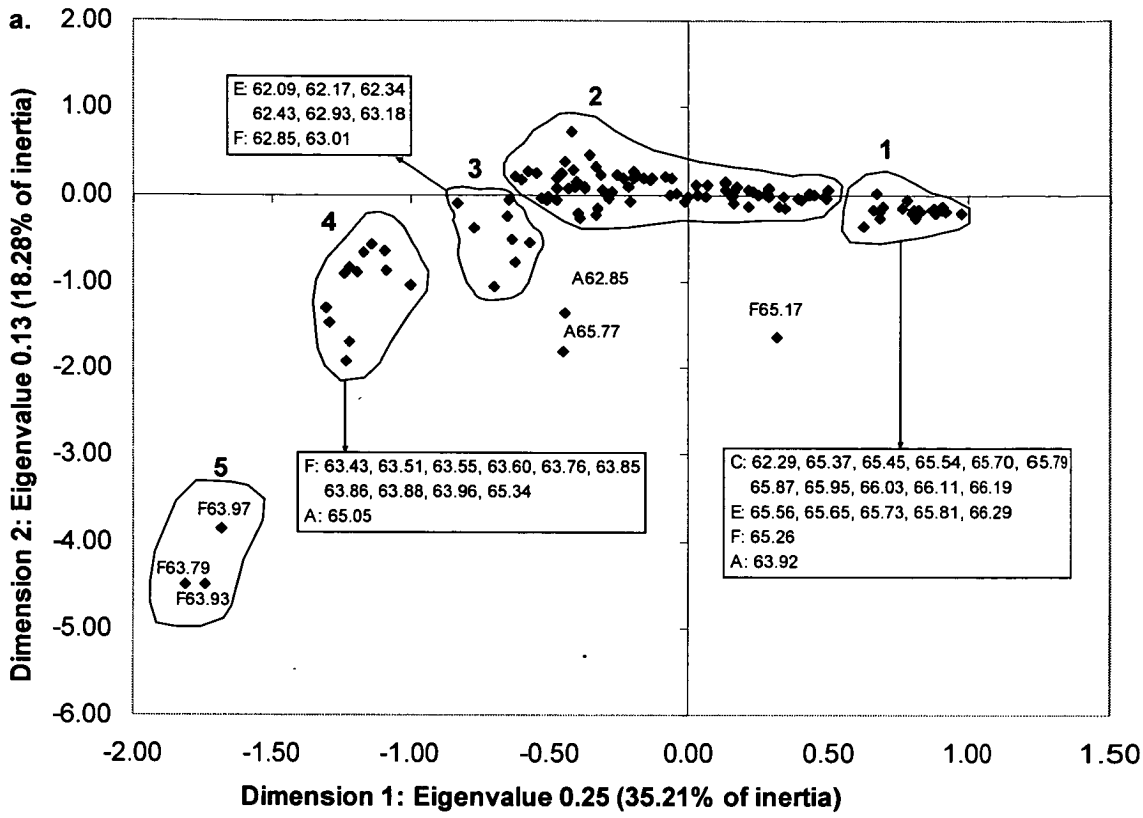


Figure 5.8. Day indicator taxa identified by applying Dufrene and Legendre's (1997) indicator value technique to clusters obtained using the Bray-Curtis dissimilarity measure and Un-Weighted Pair Group Average linkage UPGA. Taxa indicated for each sample grouping had indicator values ≥ 25%, which meant that they were present in at least 50% of samples in a group and that their relative abundance in that group was at least 50%. Maximum indicator values are in bold.

Table 5.5. Average abundance (individuals.m^{-3}) of zooplankton taxa occurring in ≥ 20% of **day** samples, for the 4 clusters identified using the Manhattan Metric (Figure 5.7c). Differences between clusters were investigated using ANOVA, performed on $\log_{10}(x+1)$ transformed abundance levels. Significance levels are indicated by F and p. Newman-Keuls multiple range tests were performed to identify inter-cluster difference in species abundance levels. Significantly higher abundance levels are in bold and underlined. * $p < 0.01$, *** $p < 0.0001$.

Taxon	Cluster 1 (n=69)	Cluster 2 (n=42)	Cluster 3 (n=7)	Cluster 4 (n=4)	F	p
Foraminifera	9.82	**50.08**	**49.53**	**41.17**	44.39	***
Phalacrophorus pictus	0.52	0.67	0.37	0.00		
***Limacina* spp.**	9.82	**30.08**	**60.44**	**25.27**	13.85	***
Clausocalanus laticeps	0.82	0.74	**3.71**	0.00	4.56	*
Ctenocalanus citer	2.33	**10.53**	**15.81**	2.63	15.93	***
Oithona similis	20.04	191.59	**519.84**	35.33	64.54	***
***Oncaea* spp.**	0.71	**7.53**	**2.94**	**6.05**	26.84	***
Rhincalanus gigas	0.20	1.79	0.55	**3.35**	11.39	***
Thysanoessa macrura	0.66	0.28	0.27	0.00		
Appendicularia	32.01	211.43	250.90	**794.02**	57.12	***



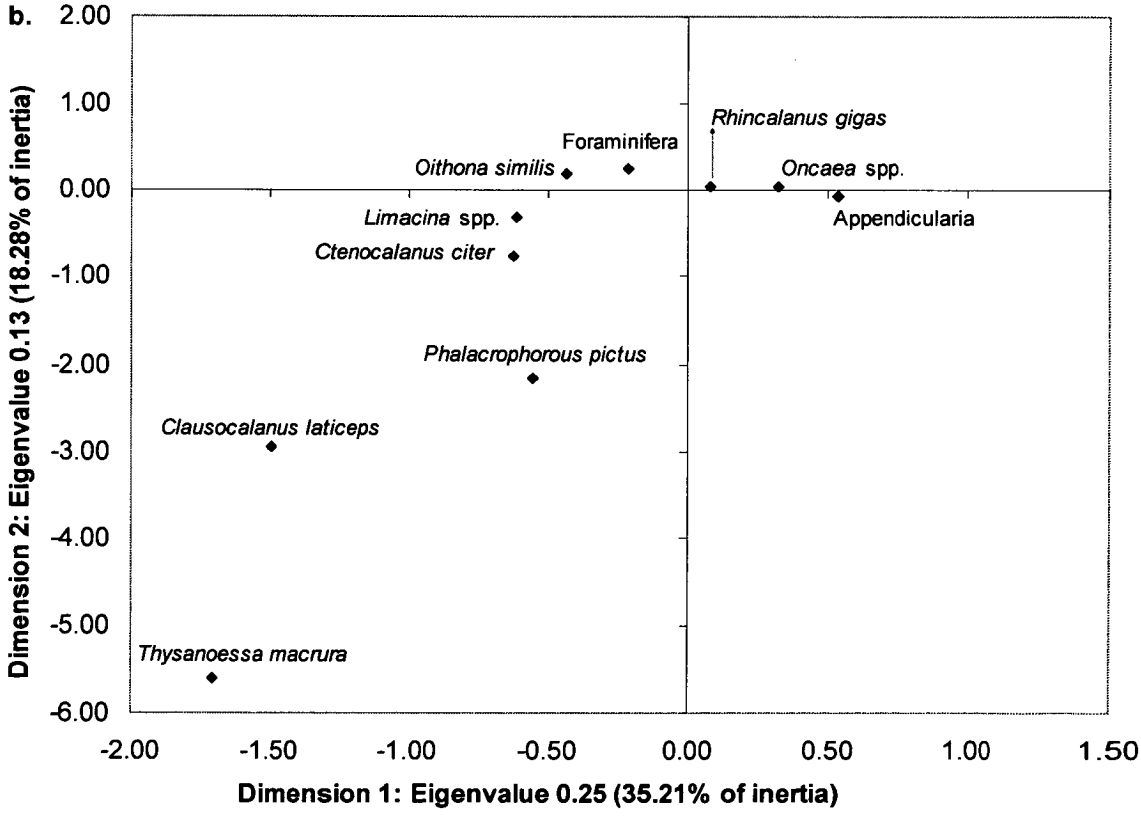


Figure 5.9. Ordination of **a.** samples and **b.** taxa using the first two dimensions of the Correspondence Analysis, based on taxa occurring in ≥ 20% of **day** samples.

between 63°S and 64°S and was therefore similar to Cluster 6 of the Bray-Curtis analysis. *Phalacrophorus pictus*, *C. citer* and *C. laticeps* appeared to be important community components. Group 5 included Transect F samples from 63.79, 63.93 and 63.97°S which were characterised by high proportions of *T. macrura*. In both the day and night data sets there was little change in the proportional contribution of dominant taxa to community composition in Transects A to D. However, by Transects E and F a substantial shift in community structure had occurred.

5.3.3. Seasonal Zooplankton Abundance

Total zooplankton abundance was low on Transect A (average = 95 ind.m^{-3}), but increased to reach peak levels on Transect B where the night samples averaged 1300 ind.m^{-3} (maximum = 1963 ind.m^{-3}) (Figure 5.10). Subsequent to Transect B abundance levels decreased through to Transect F where levels were similar to those recorded on Transect A. *Oithona similis* and appendicularians were the dominant contributors to total abundance and their seasonal density distributions reflected that of total levels. *Clausocalanus laticeps*, *Oncaea* spp., large calanoid copepodites (C1-3), *R. gigas* and *Ctenocalanus citer* also had a similar seasonal cycle to total levels, although the latter species showed a density increase on Transect F. *Limacina* spp. was almost absent from Transect A samples, and peaked on Transect C. Foraminiferans occurred at relatively high and consistent abundance levels on Transect B to E, but were scarce on Transects A and F. *Thysanoessa macrura* and *M. gerlachei* had comparatively consistent abundance levels across all Transects. *Calanoides acutus* (C4 to adult) occurred at low abundance on Transects A and B (night average = 0.89 ind.m^{-3}), increasing to comparatively high levels on Transects C to F (night average = 2.96 ind.m^{-3}). *Calanus simillimus* and *C. propinquus* (C4 to adult), *S. thompsoni* and *E. superba* all reached peak densities on Transect F, and the latter two species were completely absent from Transect A. Total abundance was typically higher at night, with the only major exception occurring on Transect D where day abundance was equivalent to night levels on Transect C and vice versa. Most taxa demonstrated strong diel variation in abundance levels, reflecting day-time migration out of the surface waters. Foraminiferans, *Oncaea* spp. and appendicularians had relatively high day abundance levels with the latter taxon occurring at highest densities on three of the day transects. *Salpa thompsoni*,

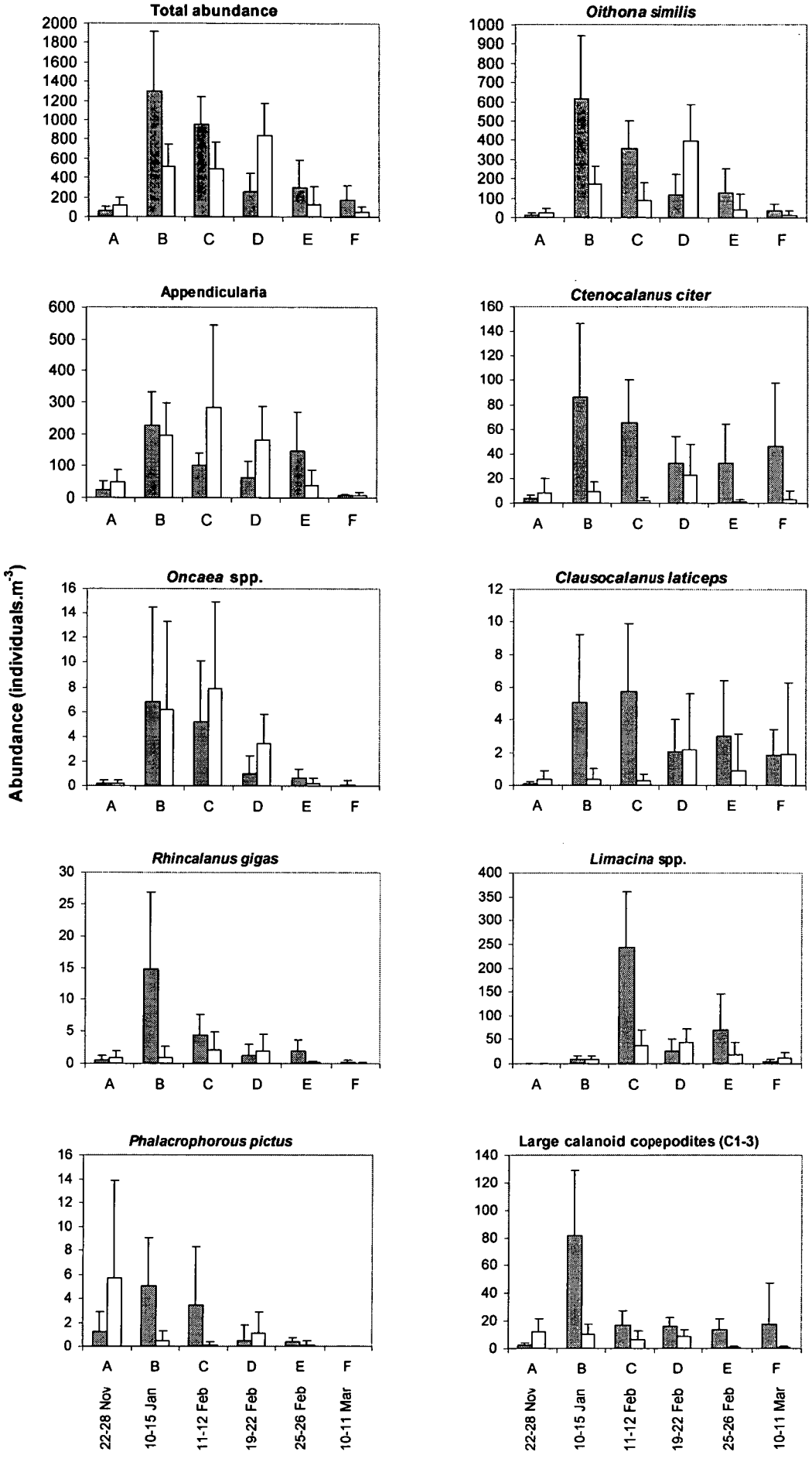


Figure 5.10. *continued overleaf...*

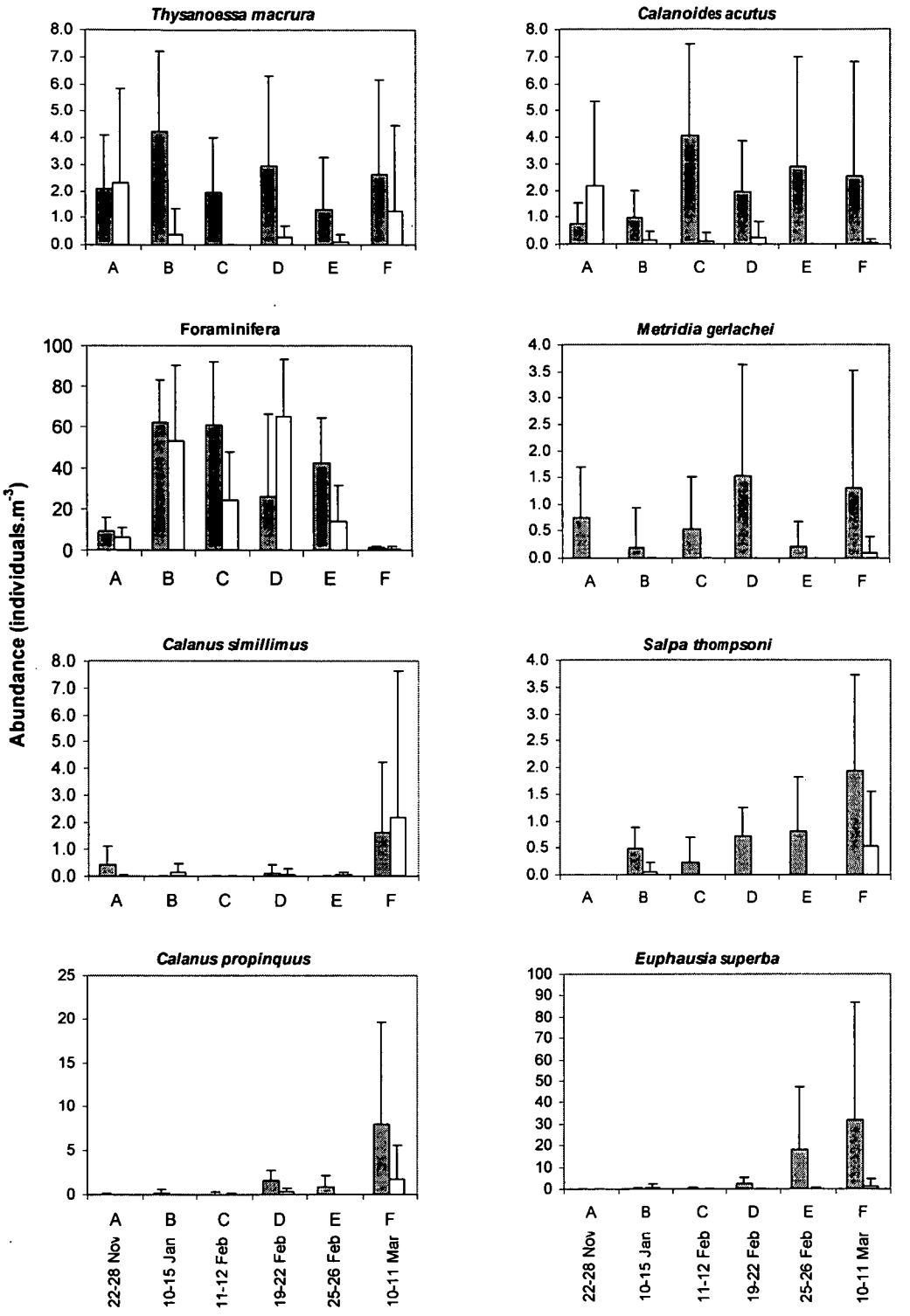


Figure 5.10. Average densities (individuals.m^{-3}) and standard deviations of major zooplankton taxa / groups for each of the six transects completed between November 2001 and March 2002. Dark bars illustrate night levels and open bars illustrate day levels.

M. gerlachei and *E. superba* were typically absent from the surface waters during the day.

5.4. Discussion

5.4.1. Study Area

The study area was bisected by the Southern Boundary (SB) of the Antarctic Circumpolar Current (ACC), and this front was associated with the steepest environmental gradients in the SIZ. The SB separates the comparatively warm, eastward flowing ACC to the north from the cold westward flowing Coastal Current (CC) to the south. A feature of the region between 140°E and 150°E is the southward introduction of part of the ACC across the SB into the CC (Bindoff et al. 2000). In east Antarctica the maximum sea-ice edge is strongly correlated with the oceanographic environment and particularly the location of the Southern Boundary (SB) of the Antarctic Circumpolar Current (ACC) (Nicol et al. 2000a). The SIZ is narrowest where the SB is closest to the coast, bringing the warmer ACC water further south. Historically, maximum sea-ice extent in east Antarctica is attained in September / October (Worby et al. 1998), and at 140°E averages 62.60°S (Figure 5.1). Sea-ice retreat begins in November, and at the time of the 22-28 November transect in this study the southern edge of the sea-ice was at ~ 62.50°S (ship-board observations). Satellite data indicated that the ice-edge retreated rapidly in 2001 (Hirawake et al. 2003), and the transect was ice-free by the middle of December, remaining so until at least the end of the final transect (11 March 2002).

The retreat of the ice-edge was coincident with the warming of the surface waters. Ship-board data on the composition and development of phytoplankton communities during the survey are not yet available but SeaWiFS data have provided insight into the development of phytoplankton biomass during the survey period (Hirawake et al 2003). Chlorophyll *a* was low in October (< 0.3 $mg.m^{-3}$) in the open water to the north of the ice-edge, but rapidly increased to 1-5 $mg.m^{-3}$ by the end of December, near the sea ice edge and in open water at and south of the Southern Boundary (SB). On 30 December a phytoplankton bloom was evident along 140°E, between ~ 65°S and 66°S, with biomass levels of 10-40 $mg.m^{-3}$. At the end of January blooms with chlorophyll *a* biomass 10-16 $mg.m^{-3}$ were observed along 140°E, centred at ~ 65°S. North of 65°S chlorophyll *a* was ~ 3 $mg.m^{-3}$,

decreasing to ~ 0.3 $mg.m^{-3}$ at 62°S. Chlorophyll *a* remained relatively high south of the SB in February (1-2 $mg.m^{-3}$), however, by March had decreased to < 0.5 $mg.m^{-3}$. The highest chlorophyll *a* levels occurred south of the SB in all SeaWiFS images. Observations from the CPR samples indicated that diatoms, principally *Thalassiothrix antarctica* and *Nitzschia kerguelensis* (K. Westwood, personal communication), were an important component of the phytoplankton community, being abundant in all January and February samples and declining in March. The presence of diatoms may have contributed significantly to the high densities of *Oithona similis* (Section 4.4.5).

5.4.2. Spatial patterns

The primary focus of Chapters 5 and 6 is the seasonal succession of zooplankton communities, however spatial variation needs to be considered due to the biogeographic influence of oceanographic fronts in the study area (Chapter 4). Although in Chapter 5 the potential influence of latitudinal variation on observed seasonal patterns was reduced by limiting the analysis to samples south of the northern branch of the SF, the study area was bisected by the SB of the ACC. Chapter 4 demonstrated that the SB separated two distinct communities within the SIZ along 140°E, and this was reaffirmed by the 25-26 February transect in the present chapter. No cross frontal variation was evident in night samples from the 22-28 November and 10-11 March transects, with single communities spanning the SB. However, inspection of cluster dendograms showed that this was a function of the dissimilarity levels chosen in the seasonal study, and that samples to the north and south of the SB were separated on both of these transects at a lower level of dissimilarity than that used for the purpose of the seasonal analysis (Appendix 3). Although day samples did not provide a complete picture of community structure, due to the migration of many taxa out of the surface waters, they gave more extensive coverage of the region south of the SB. Presence / Absence analysis demonstrated distinct communities to the north and south of the SB on 10-15 January. Conversely, on the 22-28 November and 11-12 February transects the same community occurred on either side of this front. However, as in the night sample analysis, closer inspection of cluster dendograms showed that this was a function of the dissimilarity levels chosen in the seasonal study (Appendix 3).

The distributions of some species were strongly correlated with the SB. Adult *Euphausia superba* were principally collected to the south of the SB, in the cooler waters of the Coastal Current. Similarly, after the retreat of the sea-ice, the ice associated copepod *Stephos longipes* (Schnack-Schiel et al. 1995) was only found south of the SB. *Calanus simillimus* was principally found to the north of the SB, and although widespread, this species is most characteristic of the Sub-Antarctic and Polar frontal Zones (Atkinson and Sinclair 2000, Chapter 4). However, the major community components typically occurred both to the north and south of the SB and community differences were based almost entirely on variations in the abundance levels of common taxa. For example, the densities of small copepods were consistently highest in the north of the survey area, concurring with Chiba et al. (2001) and Chapter 4.

An important spatial feature of the zooplankton communities was that of small-scale patchiness, most evident in abundance levels (Manhattan Metric) in January and early February, but more evident in species composition and the proportional composition of communities in late February and March. Two mesoscale oceanographic processes may have contributed to both similarities in community structure and the patchiness observed in the study area. East Antarctica has been shown to be a region of high eddy occurrence, generated by northward excursions of the coastal current due to local bathymetry (Wakatsuchi et al. 1994). Hirawake et al. (2003) demonstrated that in the vicinity of 140°E eddies from the CC were transported north of the SB into the ACC. Secondly, as pointed out in Section 5.4.1, water from the ACC is transported south of the SB between 140°E and 150°E (Bindoff et al. 2000). It is possible that this was responsible for samples with characteristics of the northern *C. simillimus* community occurring to the south of the SB in the night samples. Therefore, although the SB was the dominant physical feature influencing community structure, the above two mesoscale processes may play an important role in generating small-scale heterogeneity i.e. patchiness and cross-frontal exchange.

5.4.3. Seasonal Community Succession

The four multivariate analyses used for this study each provided different insights into the seasonal succession of community structure. Total abundance levels were low on the 22-28 November transect and this was reflected by the Manhattan

Metric, and the low number of indicator species identified by IndVal analysis. Species composition clearly separated the early season samples from those collected on subsequent transects. Differences in the sampling capabilities of NORPAC nets and the CPR would have contributed significantly to this. The NORPAC nets used on the 22-28 November transect collect soft bodied plankton more efficiently than the CPR (Hunt and Hosie 2003, Chapter 3), and such taxa were an important component of the November community. However, the presence of the sea-ice associated copepod *Stephos longipes*, in both night and day samples, indicated that the 22-28 November community was directly influenced by the presence of sea-ice.

Presence / Absence analysis demonstrated that a change in species composition had occurred by 10-15 January, most strongly evident in the night samples. Numerous species occurred at high frequencies after being absent or rare on the 22-28 November transect, including *Calanoides acutus*, *Thysanoessa macrura*, *Limacina* spp., *Clausocalanus laticeps* and *Rhincalanus gigas*. The aforementioned taxa, together with *Oithona similis*, *Ctenocalanus citer*, foraminiferans, and appendicularians were present as ubiquitous community components throughout January, February and March. The most significant change between 22-28 November and 10-15 January was the order of magnitude increase in total zooplankton abundance to peak levels for the survey (average = 1300 ind.m^{-3}). Although this increase was reflected by the abundance levels of most taxa, the Manhattan Metric demonstrated that the "Peak Community" was dominated by high densities of *Oithona similis*, the small calanoid (< 1.5 mm) copepods *C. citer* and *C. laticeps*, foraminiferans, *Limacina* spp., appendicularians and *R. gigas*, while large calanoid copepodites (C1-3) were also important contributors. Indeed, this group of taxa, or part thereof, was the major contributor to total zooplankton abundance throughout the study, during both day and night, as illustrated by their seasonal cycle of abundance corresponding with total levels.

The seasonal decrease in abundance of "Peak Community" taxa coincided with an increased frequency of occurrence and abundance of *Salpa thompsoni*, *Euphausia superba* larvae, and the large calanoid copepods *Metridia gerlachei*, *Calanus propinquus* (C4-Adult) and *Calanus simillimus* (C4-Adult). This community shift was most strongly apparent in the night data set and was first observed in the high frequency and abundance of *S. thompsoni*, *E. superba* larvae, *M. gerlachei*, *C. propinquus* and *C. simillimus* in night samples north of ~ 62.75°S on the 19-22 February transect. Presence / Absence analysis of night data indicated

the occurrence of these taxa in the central samples (~ 63.70°S to 64.70°S) of the 25-26 February transect. However, both the Bray-Curtis measure and Manhattan Metric demonstrated that the abundance levels of "Peak Community" taxa remained relatively high and continued to dominate community structure in these samples. Conversely, "Peak Community" taxa occurred at low abundance in 25-26 February samples south of the SB while *E. superba* larvae were abundant. All three cluster analyses showed that *S. thompsoni*, *E. superba* larvae, *M. gerlachei* and *C. propinquus* had become defining components of the central samples (64-65°S) by 10-11 March, while the samples north of 62.70°S were characterised by the predominantly Sub-Antarctic / Polar Frontal Zone copepod *C. simillimus*, *S. thompsoni, C. pyrimidata* and the salp associated amphipod *Vibilia* sp. (Madin and Harrison 1977).

A similar seasonal succession in community structure was observed in the day samples, although becoming apparent later in the season than at night. Presence / Absence analysis demonstrated that the "Peak Community" taxa *O. similis*, appendicularians, foraminiferans, *Limacina* spp. and *C. citer* dominated most samples collected between 10-15 January and 25-26 February. Community differences during this period were largely due to variations in the abundance levels of these taxa. A similar end of season community to the night samples was observed in a small number of 10-11 March samples, featuring a strong representation of large calanoid copepods and the presence of *S. thompsoni* and *E. superba* larvae. However, these taxa were typically absent during the day, and the majority of day samples were characterised by low abundance, species poor communities, indicative of the diel migration of many taxa out of the surface waters. The only marked exception was the day samples centred at ~ 63.60°S on 19-22 February where abundance levels and taxonomic composition were equivalent to night samples from 11-12 February. Conditions may therefore occasionally favour day-time occupation of the surface waters e.g. high surface chlorophyll *a* biomass (Atkinson et al. 1996). More intensive measurement of physical and biological parameters is required to elucidate the cause of such variation in the diel cycle.

Correspondence Analysis highlighted the seasonal shift in community structure. In the night samples this shift was strongly associated with the increasing proportional contributions of *S. thompsoni*, *E. superba* larvae, *M. gerlachei*, and C4-Adult *C. propinquus* through February to March. These taxa were excluded from the day analysis due to their occurring in < 20% of samples, the latter reflecting the day-

time descent of a large proportion of their populations below the sampling depth of the CPR. The common feature of the community shift observed in the two data sets was therefore the seasonal decrease in the densities of small copepods, appendicularians, *Limacina* spp. and foraminiferans, resulting in total abundance returning to November levels. Total abundance at the beginning and end of the survey was < 15% of maximum levels in both night and day samples. In the Atlantic sector of the Southern Ocean average abundance levels of copepods in winter (June to August) has been found to be 24% of summer levels in the top 1000 m of the water column (Atkinson and Sinclair 2000). Therefore the seasonal migration of taxa to deeper layers (Schnack-Schiel and Mizdalski 1994, Atkinson and Sinclair 2000) was probably an important factor in the low zooplankton densities observed in spring (22-28 November) and early autumn (10-11 March). It is possible that competition, particularly with salps and krill larvae, contributed to the seasonal density decline. *Salpa thompsoni* has been observed to graze up to 100% of daily primary production (Perissinotto and Pakhomov 1998).

5.4.4. Population Cycles

The seasonal community succession was strongly influenced by species population cycles. *Calanoides acutus*, *Calanus propinquus* and *Calanus simillimus* all reproduce in the spring, although the timing of the respective species is staggered (Voronina et al. 1978, Atkinson 1991). The peak abundance levels of early copepodites stages (C1-3) on the 10-15 January transect represented the developing spring generations of these species. The subsequent decrease in C1-3 abundance levels corresponded with the increased occurrence of C4-Adult *C. acutus*, *C. simillimus* and *C. propinquus*. The single peak in densities of C4-Adult *C. propinquus* and *C. simillimus* in March indicated that these species had one year life-cycles while the occurrence of C4-Adult *C. acutus* on all transects supports the two year life-cycle proposed by Takahashi (2003) for a component of this species population. Of these three calanoid copepods, C4-Adult *C. acutus* increased in abundance earliest in the season reflecting the earlier commencement of its spring reproduction (Atkinson 1991). In the region north of the SB there appeared to be a latitudinal gradient in population development. The seasonal increase in densities of C4-Adult *Calanoides acutus*, *Calanus propinquus* and *Calanus simillimus* occurred first in the north and progressed southwards through the season. A latitudinal

gradient in the timing of seasonal population cycles has been noted previously (Voronina et al. 1978, Marin 1987, Atkinson 1991, Ross et al. 1996, Atkinson et al. 1997), and may be an important source of zonal variation in community structure at any one time.

Salpa thompsoni survives the winter deep in the water column in an asexual solitary stage (Foxton 1966, Ross et al. 1996). The solitary stages rise to the surface in spring and summer, and begin budding to produce aggregate forms. The absence of *S. thompsoni* from the 22-28 November samples, including samples to 150 m (Appendix 4), may therefore have been due to their deep early season distribution and / or low densities. Increased densities of *Salpa thompsoni* first appeared in the north of the study area, and progressed southwards though the season, demonstrating a similar seasonal lag to *C. acutus*, *C. propinquus* and *C. simillimus*. Salps are considered to favour low chlorophyll environments (Harbison et al. 1986, Perissinotto and Pakhomov 1998). After the extremely high early season phytoplankton biomass (Hirawake et al. 2003), the seasonal biomass decrease began first in then north of the survey area, and progressed southwards. The southward increase in *S. thompsoni* densities through the season therefore appeared to be due to improving trophic conditions for this species.

The occurrence and distribution of *E. superba* was strongly tied to its population cycles. Post-larval *E. superba* are expected to be sampled poorly by the CPR due their large size and efficient net avoidance, and adult specimens were only recorded in 10-15 January samples, predominantly south of the SB, and at low densities. Previous studies in this region, completed with traditional nets (RMT) between January and March, have found post-larval *E. superba* to be concentrated south of the SB and particularly at or on the continental shelf (Chiba et al. 2000, Nicol et al. 2000a,b). Given that it takes ~ 25 days to progress from egg-laying to calyptopis I (Hofmann et al. 1992), the adults recorded on the 10-15 January may have represented surface spawning aggregations in the deep waters north of the continental shelf (Siegel and Harm 1996, Nicol et al. 2000b). All *E. superba* recorded from 19-22 February onwards were larval stages. Their appearance in 19-22 February samples marked their ontogenetic migration into the surface waters (Schnack et al. 1985). The wide distribution of larvae to the north and south of the SB concurred with the distributions observed by Nicol et al. (2000a,b).

5.4.5. Implications

The narrow SIZ off the Adelie Land coast may provide important insights into the future impacts of climate change, including the ecosystem changes that can be expected to occur in association with reduced sea-ice extent. Of particular relevance is the influence of sea-ice extent on the contributions of *E. superba* (krill) and *S. thompsoni* (salps) to pelagic biomass. These two species are considered to be key components of the Antarctic pelagic ecosystem, through their multiple roles as grazers, predators and prey species (Huntley et al. 1989, Smetacek et al. 1990, Nicol 1994). Krill recruitment success has been shown to be positively correlated with sea-ice extent (Siegel and Loeb 1995, Loeb et al. 1997, Chiba et al. 1998). The krill life-cycle is intimately linked to the seasonal sea-ice, and its decline can therefore be seen as a reduction in krill habitat (Smetacek et al. 1990). Conversely, salps have been observed to have high biomass after winters of low sea-ice extent (Loeb et al. 1997). These authors hypothesised that high early season grazing by salps during periods of low sea-ice extent may significantly deplete chlorophyll *a* stocks and hence contribute to low krill recruitment by inhibiting this species' gonadal development and spawning success.

The low krill biomass observed in the vicinity of 140°E, while being higher to the west (between 80-115°E) where sea-ice was more extensive (Nicol et al. 2000a,b), concurs with the krill / sea-ice relationship presented by Loeb et al. (1997). Along 140°E salp densities only increased towards the end of the season (March), and so little spring / early summer competition with adult krill populations would have occurred. By March, however, salps were distributed both to the north and south of the SB. The southward penetration of salps into the SIZ off Adelie Land has been observed previously, with densities of up to 30 ind.m^{-3} and comprising 44% to total zooplankton abundance (Casareto and Nemoto 1986, Chiba et al. 1998, Chiba et al. 2000, Hosie et al. 2000). The seasonal population cycle of salps in the study area therefore brings them into direct interaction with the developing krill larval stages in February and March. Although they had overlapping distributions, occurring to both the north and south of the SB, IndVal analysis indicated that their distribution centres differed, krill larvae occurring principally to the south and salps to the north of the SB. It is probable that this was principally a reflection of physical separation and environmental preferences. However, in view of their high grazing rates (Perissinotto and Pakhomov 1998), competition with salps may have significantly impacted on krill recruitment success. Whether influenced by

one or a combination of poor habitat and competition with other zooplankton, the recruitment of krill larvae off the Adelie Land coast has been demonstrated to be poor (Chiba et al. 2000). The low krill biomass observed by all surveys in this region, including the Discovery Expeditions (1926-39), is evidence that low recruitment is a consistent feature (Marr 1962, Mackintosh 1973, Nicol et al. 2000a,b).

Krill have been shown to exert significant top down control on copepod populations through a combination of competition and predation (Atkinson and Snyder 1997, Atkinson et al. 1999, Atkinson et al. 2001). The low krill biomass off the Adelie Land coast, particularly the SIZ north of the SB, may therefore have contributed indirectly to the dominance of small grazers (including *O. similis*, small calanoid copepods, *Limacina* spp., and appendicularians) during the spring bloom,. The community characteristics of this low sea-ice environment have potentially significant implications for biogeochemical cycling. Krill contribute directly to vertical flux through the production of large heavy faecal pellets (Smetacek et al. 1990, Priddle et al. 2003), however, a potentially large proportion of the carbon harnessed by primary production is respired back into the atmosphere by this species' vertebrate predators (Huntley et al. 1991). Although copepod dominated communities are considered to be highly retentive, they have a relatively low grazing impact on large diatoms species (Gonzalez and Smetacek 1994, Dubischar and Bathmann 1997, Dubischar et al. 2002). Therefore, during diatom blooms, such as those observed during the 2001 / 2002 summer season, it is possible that a large amount of the carbon harnessed by primary production is transferred to the sea-floor through direct sedimentation of diatom cells (Smetacek et al. 1990, Longhurst 1991, Honjo et al. 2000). Conversely, during periods of low phytoplankton biomass (end of season) vertical flux may be maintained by salp faecal pellets (Smetacek et al. 1990). Differences in community structure between high and low sea-ice environments, influenced by a combination of physical and biological interactions, may therefore have a significant bearing on vertical flux and related atmospheric feedback. Sediment trap studies comparing vertical flux in regions of high and low sea-ice extent along the east Antarctic coast would provide valuable insights into the influence of zooplankton community structure on these processes.

5.4.6. Summary

A strong seasonal succession was evident in the zooplankton community. Zooplankton abundance was lowest on 22-28 November (average = 96.23 ind.m^{-3}), when practically the entire transect was covered by sea-ice, and this was reflected by the abundance levels of most taxa. By 10-15 January total abundance had increased to its maximum levels for the season, reaching a night-time peak of 1963 ind.m^{-3}, and were dominated (during both night and day) by *Oithona similis*, the small calanoid (< 1.5mm) copepods *Ctenocalanus citer* and *Clausocalanus laticeps*, foraminiferans, *Limacina* spp., appendicularians, *Rhincalanus gigas* and large calanoid copepodites (C1-3). These "Peak Community" taxa, along with the less abundant *Thysanoessa macrura*, maintained a ubiquitous presence in samples throughout the survey, although, with the exception of appendicularians, densities appeared to be greatest north of the SB. After the 10-15 January transect abundance levels gradually decreased through to March 10-11 where levels were equivalent to those recorded on 22-28 November. This decrease in total abundance was characterised by a shift in community structure, dominated by the declining densities of "peak community" taxa, but associated with the increased contribution of C4 to Adult *Calanoides acutus*, *Calanus propinquus* and *C. simillimus*, increased abundance of *Salpa thompsoni*, and the rise of *E. superba* larvae to surface waters. The seasonal community cycle appeared to be determined by the interlinked components of low sea-ice extent and the southward projection of the ACC along 140°E. The relatively warm ACC waters, together with low krill biomass, favoured high densities of small grazers during the January / February bloom conditions. The persistence of relatively warm surface waters in March and the seasonal decrease in chlorophyll *a* biomass provided favourable conditions for salps which were able to penetrate south of the Southern Boundary. The overlap of salp distributions with the developing krill larvae may be a contributing factor to low recruitment success of krill observed in this region.

Chapter 6

Zooplankton community succession in the Southern Ocean south of Tasmania, Australia. Part II: the Sub-Antarctic to Polar Frontal Zones

6.1. Introduction

The Sub-Antarctic Zone (SAZ) and the Polar Frontal Zone (PFZ) are the two northernmost zones of the Antarctic Circumpolar Current (ACC) (Lutjeharms and Valentine 1984, Nowlin and Klinck 1986). They are regions with relatively uniform physical characteristics, delineated by distinct circumpolar fronts, across which the majority of inter-zonal change occurs (Orsi et al. 1995). The SAZ is located between the Sub-Tropical Front (STF) in the north and the Sub-Antarctic Front (SAF) in the south, while the PFZ extends southwards from the SAF to the Polar Front (PF). Together, the SAZ and PFZ comprise approximately 60% of the area of the Southern Ocean (> 50% of this the SAZ) (Moore et al. 2000), and they therefore represent the most typical environment for Southern Ocean zooplankton. These two zones are transitional between Antarctic surface waters in the south and Sub-Tropical waters to the north, and as such the SAZ is warmer and more saline than the PFZ (Orsi et al. 1995). Their distinct physical and biogeochemical (e.g. high silicate in the PFZ) properties (Orsi et al. 1995, Rintoul and Trull 2001) have a significant bearing on zonal biology and ecology (Deacon 1982), and despite sharing many community components, the two regions are considered to be biogeographically distinct (e.g. Tarling et al. 1995, Pakhomov and McQuaid 1996, Wright et al. 1996, Errhif et al. 1997, Fiala et al. 1998).

Physically the Southern Ocean south of Australia differs from other sectors, being characterised by multiple branches of the SAF and PF (Sokolov and Rintoul 2002). The region conforms to the High Nutrient Low Chlorophyll (HNLC) stereotype of the Southern Ocean (Banse 1996, Landry et al. 2002, Trull et al. 2001c). SeaWiFS data (Rintoul and Trull 2001, Moore and Abbott 2002) and *in situ* measurements from ship based traverses (Yamaguchi and Shibata 1982, Kopczynska et al. 2001, Trull et al. 2001b) have demonstrated that surface chlorophyll *a* concentrations typically have a seasonal range of between 0.1 and 0.4 $mg.m^{-3}$. A characteristic of the PFZ in this region, and to a lesser degree the SAZ, is the seasonal occurrence of a Sub-Surface Chlorophyll Maximum (SCM), with

chlorophyll *a* biomass ranging between 0.4 and 0.7 $mg.m^{-3}$ (Yamaguchi and Shibata 1982, Kopczynska et al. 2001, Parslow et al. 2001). The low iron concentrations characteristic of the deep ocean basin south of Australia are considered to play a major role in maintaining the generally low chlorophyll *a* concentrations in this region (de Baar et al. 1995, Moore and Abbott 2002), and both higher dissolved iron and phytoplankton concentrations have been measured north of the SAZ, in the Sub-Tropical zone (40°S to 45°S) along 140°E (Sedwick et al. 1997, Kopczynska et al. 2001).

By comparison to phytoplankton, the zooplankton has been poorly studied in the SAZ and PFZ south of Australia. Analysis of a single Continuous Plankton Recorder (CPR) transect along 140°E demonstrated that the multiple branches of the SAF and PF significantly influence the zonal structure of communities (Chapter 4). However, to my knowledge no study has investigated the seasonal cycle of zooplankton in this region. The importance of seasonal data to both long-term monitoring and the understanding of ecosystem functioning has been outlined in Section 5.1.1. In this light the aim of Chapter 6 was to identify the seasonal succession of zooplankton communities in the SAZ to PFZ by multi-variate analysis of the data collected during the 2001 / 2002 Australian-Japanese collaborative study.

6.2. Methods

6.2.1. Data Collection

Between October 2001 and March 2002 six transects sampling the zooplankton were completed at approximately monthly intervals, between the STF and the northern Polar Front (PF-N) in the region south of Australia. Details of vessels used for each transect and sample locations are presented in Figure 6.1 and Table 6.1. Transect A (October) sampled the region between 54.00°S and 47.00°S and from 132.7°E in the south to 142.6°E in the north. Transects B and C (November and December) sampled diagonally between approximately 145°E and 142.5°E, from 54°-47°S and 53.55°-51.29°S respectively. Transects D, E and F (January, February and March) were completed along the 140°E meridian, between approximately 54.00°S and 47.00°S.

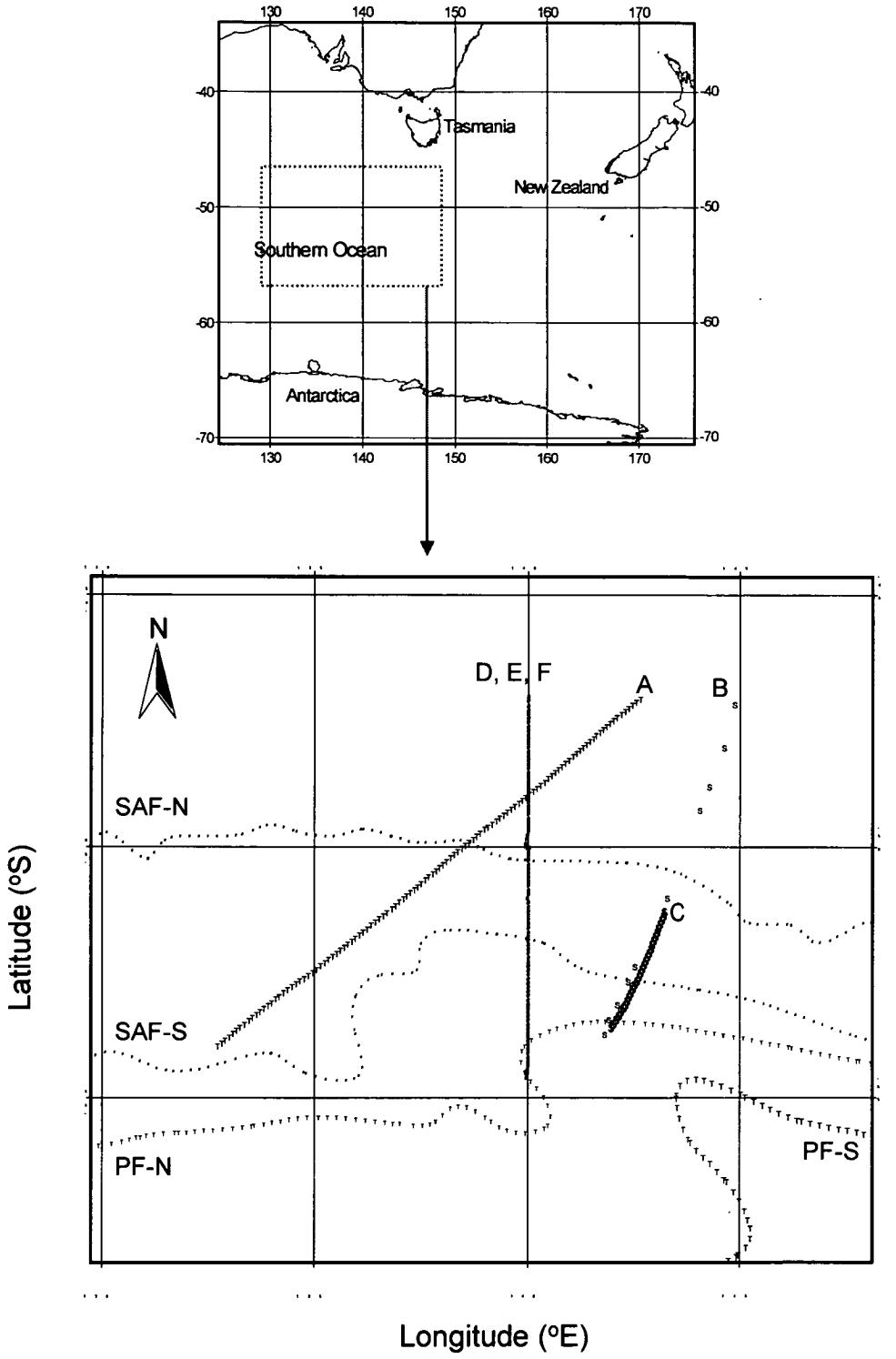


Figure 6.1. Map of study area, indicating the position of zooplankton transects A (Δ), B (○), C (▲), and D to F (●).The average position of fronts in the study area are those of Sokolov and Rintoul (2002). SAF-N – northern Sub-Antarctic Front; SAF-S – southern Sub-Antarctic Front; PF-N – northern Polar Front, PF-S – southern Polar Front.

Zooplankton samples were collected with a CPR on all transects with the exception of November when a NORPAC net was used, sampling at ten stations spaced an average of 0.73° apart (Figure 6.1). Both the CPR and NORPAC nets were fitted with 270μm mesh. Based on the low inter-vessel depth variation recorded by Hays and Warner (1993), the sampling depth of the CPR from the RV *Hakuho Maru*, RV *Tangaroa* and RV *Shirase* would have been within a few meters of the ~ 10.5m recorded from the RV *Aurora Australis* (Hunt and Hosie 2003). As no flowmeter was attached to the CPR filtration efficiency was assumed to be 100%. The NORPAC net was hauled vertically between 0 and 20m to make these samples comparable with those collected by the CPR. A mechanical revolution counting flowmeter (Rigosha and Co., Ltd, no. 5571-A) was secured across the mouth of the NORPAC net for volume filtered calculation.

Table 6.1. Details of monthly transects conducted south of Tasmania between October 2001 and March 2002.

Transect	Ship	Net	Sample period	Latitude	Longitude
A	*Aurora Australis*	CPR	17-19 October 2001	54.0-47.0°S	132.7-142.6°E
B	*Aurora Australis*	NORPAC	2-13 November 2001	47.0-54.0°S	144.9-141.9°E
C	*Aurora Australis*	CPR	11-12 December 2001	53.6-51.3°S	142.0-143.3°E
D	*Hakuho Maru*	CPR	17-19 January 2002	54.6-47.0°S	140°E
E	*Tangaroa*	CPR	7-9 February 2002	47.0-54.0°S	140°E
F	*Tangaroa*	CPR	2-3 March 2002	54.0-47.0°S	140°E

The collection, treatment and processing of samples followed the protocol in Section 2.3.2. The entire contents of al CPR samples was identified and enumerated. NORPAC samples were sub-sampled using a box splitter and aliquots ranged between one-half and one-eighth of the total. Identification was to species and stage level wherever possible, and followed the protocol in Section 2.3.3. Copepodite stages C1 to C3 of *Calanus simillimus* and *Neocalanus tonsus* were not identified to species, and were grouped together as large calanoid copepodites (C1-3). *Thysanoessa macrura* and *T. vicina* were grouped as *T. macrura / vicina* due to difficulties in separating these two taxa (Kirkwood 1982), although as the majority of samples were north of the Polar Front *T. vicina* probably dominated. To facilitate comparison of the two net systems the soft bodied species identified in the NORPAC samples were placed in the same groupings used for the CPR samples i.e. hydromedusae, ctenophores, siphonophores, chaetognaths, *Limacina* spp. and

Tomopteris spp.. All *Salpa thompsoni* specimens collected were of the aggregate form. Zooplankton abundance was converted to individuals.m^{-3}.

Sea Surface Temperature (SST) and Surface Salinity (SS) were measured at one-minute intervals during each transect, and these data were used to determine the location of frontal systems within the study area. Photosynthetically Active Radiation (PAR) was measured at one minute intervals on all transects with the exception of January and February. Ocean colour estimates of chlorophyll *a* along the 140°E transect line were extracted from NASA SeaWiFS 8 day approximately 9km resolution mapped composites. Monthly average chlorophyll *a* was calculated for the regions north and south of the northern branch of the SAF-N for the period October 2001 to May 2002.

6.2.2 Data Analysis

A sample by taxon matrix was produced for the multivariate analysis of community structure comprising the November to March samples. The October samples were processed by J. Kitchener and were excluded from the multivariate analysis in order to ensure methodological consistency (e.g. taxonomic identification level). Large calanoid copepodites (C1-3) and unidentified nauplii were excluded, and the stages of other taxa were merged. Due to diel variation in zooplankton communities sampled by the CPR (Hunt and Hosie 2003), the data set was divided into night and day samples. Night was defined as samples where PAR < 100 $\mu mol.s^{-1}.m^{-2}$, or, where PAR was not measured, between sunset and sunrise. The night and day subsets comprised 110 and 208 samples respectively. Following the protocol in Chapter 5 (Section 5.2.2), the seasonal succession of zooplankton communities in the night and day data sets was investigated in terms of **1.** taxonomic composition, **2.** a dissimilarity coefficient, **3.** abundance levels, and **4.** the proportional contribution of taxa, through the application of Cluster Analysis and Correspondence Analysis. An abbreviated analysis protocol will be presented here.

6.2.2.1. Taxonomic composition

The complete species list was reduced to a Presence / Absence matrix. Sorensen's coefficient was applied to produce a dissimilarity matrix before cluster analysis using Unweighted Pair Group Average (UMPGA) linkage. The Information

Statistic (2ΔI) was calculated to identify the species primarily responsible for sample clusters (Field et al. 1982). As 2ΔI has an approximate chi-square distribution, indicator species were selected based on the 1% and 5% probability levels, corresponding with $2\Delta I > 6.635$ and $2\Delta I > 3.841$ respectively. The Information Statistic was calculated in a pair-wise fashion for cluster groupings at each level of separation.

6.2.2.2. Dissimilarity Coefficient

Cluster Analysis was performed on the full species set, after $\log_{10}(x+1)$ transformation of abundance levels, using the Bray-Curtis dissimilarity coefficient and UMPGA linkage, following the protocol in section 3.2.2.2. Dufrene and Legendre's (1997) indicator value (IndVal) analysis was applied to sample groupings at each level of separation in the cluster analysis, following the protocol in section 4.2.2. The IndVal method combined measures of group specificity (A_{ij}) and group fidelity (B_{ij}) and was thus complementary to the Bray-Curtis dissimilarity coefficient. Indicator values of $\geq 25\%$ were used, which meant that a taxon was present in at least 50% of samples in a group and that its relative abundance in that group was at least 50%.

6.2.2.3. Abundance Levels

A third cluster analysis was performed on the raw abundance data (individuals.m^{-3}) of taxa occurring in $\geq 20\%$ of samples, using the Manhattan Metric and UMPGA linkage. The Manhattan Metric (MM) calculated the distance between two samples as the sum of the differences in species abundance levels for the two sampling units being compared (Pielou 1984). As absolute abundance values were used this analysis focused on seasonal changes in the abundance levels of dominant taxa. Differences in the abundance levels of taxa between clusters were investigated by ANOVA of $\log_{10}(x+1)$ transformed abundance data. Where significant differences in abundance were detected Newman-Keuls multiple range tests were performed to identify inter-cluster differences.

6.2.2.4. Proportional Composition

The proportional contribution of taxa to community structure was investigated using Correspondence Analysis. In Correspondence Analysis the relationship between samples / rows is quantified using the X^2 distance, and consequently the resulting ordinations are a reflection of the proportional contribution of taxa to total abundance (Ortner et al. 1989). Analysis was performed on the data set reduced to species occurring in ≥ 20% of samples across the survey in order to focus attention on the dominant taxa. The Correspondence Analysis was therefore complementary to the Manhattan Metric (Section 6.2.2.4).

6.3. Results

6.3.1. Physical Environment

A transect along the 140°E meridian between 47°S to 55°S spans both the northern and southern branches of the Sub-Antarctic Front (SAF-N and SAF-S), and generally the northern branch of the Polar Front (PF-N) (Sokolov and Rintoul 2002). The surface expressions of the SAF-N and SAF-S are typically located between 50-51°S and 52-53°S respectively, and the PF-N between 53-54°S. The SAF-N was distinct on all transects, being characterised by a sharp north to south drop in both SST and SS (Figure 6.2). In October the SAF-N was located at ~ 49.50°S, but had moved northwards to ~ 49.25°S by November, and ~ 48.75°S in December. Subsequently the SAF-N appeared to move southwards, being located at ~ 49.25°S in January, ~ 50.25°S in February, and ~ 50.50°S March. The SAF-S had a weaker surface expression than the SAF-N. The SAF-S appeared to be located at approximately 53.25°S in October, south of its average position, but by November had moved northwards to ~ 52.75°S. In December the SAF-S was at ~ 52.25°S, ~ 52.75°S in January, ~ 52.50°S in February, and ~ 52.00°S in March. The PF-N was crossed only three times during the survey, at 54.75°S in October, 54.50°S in November and 54.25°S in December, and zooplankton were only sampled from this front in December. Following Chapter 4 the region north of the SAF-N was termed the Sub-Antarctic Zone (SAZ), the region between the SAF-N and SAF-S the Inter Sub-Antarctic Front Zone (ISAFZ), and the region between the SAF-S and the PF-N the Polar Frontal Zone (PFZ). The SAZ was characterised by a high degree of small

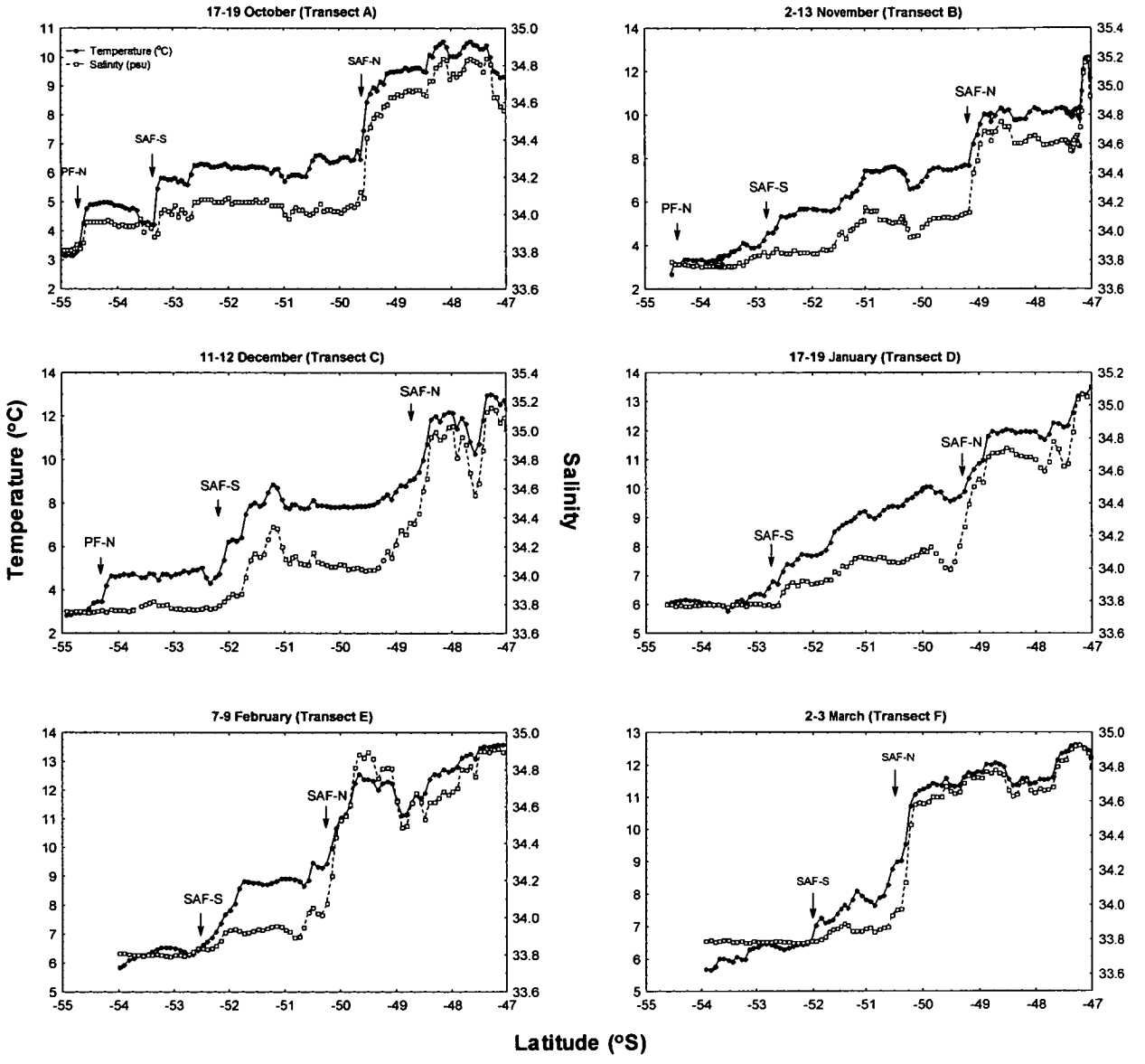


Figure 6.2. Sea Surface Temperature (°C) and Surface Salinity from the six zooplankton transects completed between October 2001 and March 2002. Note: the Y1 (temperature) and Y2 (salinity) axes have different scales.

scale heterogeneity in SST and SS reflecting the occurrence of either eddies or frontal meanders.

6.3.2. Chlorophyll *a* Biomass

Surface chlorophyll *a* biomass was < 0.2 $mg.m^{-3}$ throughout the survey area in October (Figure 6.3 and 6.4). In the SAZ levels increased sharply between October and November, from approximately 0.19 to 0.27 $mg.m^{-3}$ (Figure 6.3). Average values in this zone had a weak maximum in December and remained relatively high in January, although never averaging > 0.3 $mg.m^{-3}$. Patches of relatively high biomass (0.5 to 0.6 $mg.m^{-3}$) were observed in the SAZ between November and January, however in the latter month they were predominantly downstream (east) of the study area (Figure 6.4). Chlorophyll *a* in the SAZ decreased substantially in February but increased again in March, although remaining lower than November to January levels. The SAF-N represented a sharp boundary between relatively high surface chlorophyll *a* in the SAZ and low values in the ISAFZ and PFZ (Figure 6.4). Average values of chlorophyll *a* in the ISAFZ and PF demonstrated little seasonal change and were < 0.2 $mg.m^{-3}$ throughout the survey. Some biomass enhancement was observed at both the SAF-N and the SAF-S during all months of the survey (Figure 6.4).

6.3.3. Night Zooplankton Communities

Four sample clusters were identified using Presence / Absence analysis (Figure 6.5a). Cluster 4 separated at the 54.2% level of dissimilarity and comprised January and March samples north of the SAF-N. A large number of indicator species were identified in Cluster 4 using the Information Statistic (2ΔI), including *Paracalanus* sp., *Sapphirina* sp., *Vibilia* sp., *Thysanoessa gregaria*, *Salpa thompsoni*, *Euchaeta* sp., *Hyperia* sp., *Dairella latissima*, Platysceloidea and *Euphausia longirostris* (Table 6.2). The samples from Clusters 1 to 3 were characterised by a high frequency of *Ctenocalanus citer*. Cluster 3 separated from Clusters 1 and 2 at the 53.7% level of dissimilarity and comprised March samples north of the SAF-N, between 47.55°S and 47°S. *Calocalanus* sp., *Heterorhabdus* sp., *Metridia* spp., *Pleuromamma borealis*, Hyperid sp., *E. longirostris* and decapods all occurred at high frequency in Cluster 3. Together, Clusters 1 and 2 were

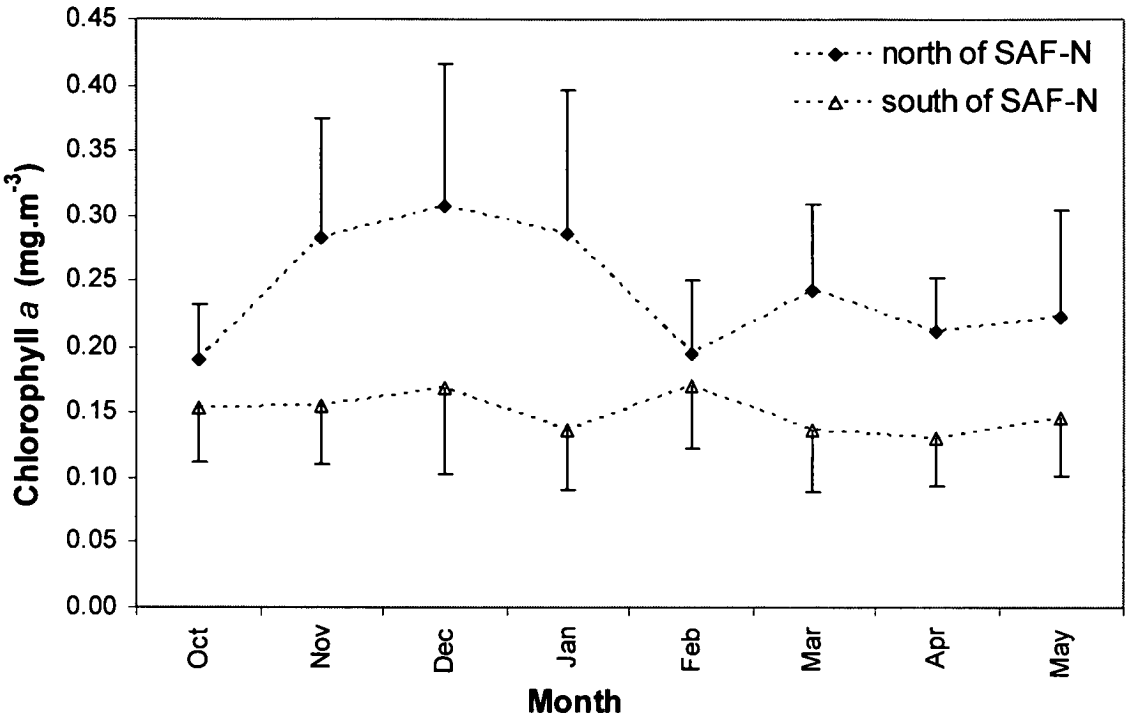


Figure 6.3. Monthly average chlorophyll *a* ($mg.m^{-3}$) and standard deviations for the period October 2001 to May 2002, and for the regions north and south of the northern branch of the Sub-Antarctic Front. Values were derived from NASA SeaWiFS 8 day, approximately 9 km resolution, mapped composites.

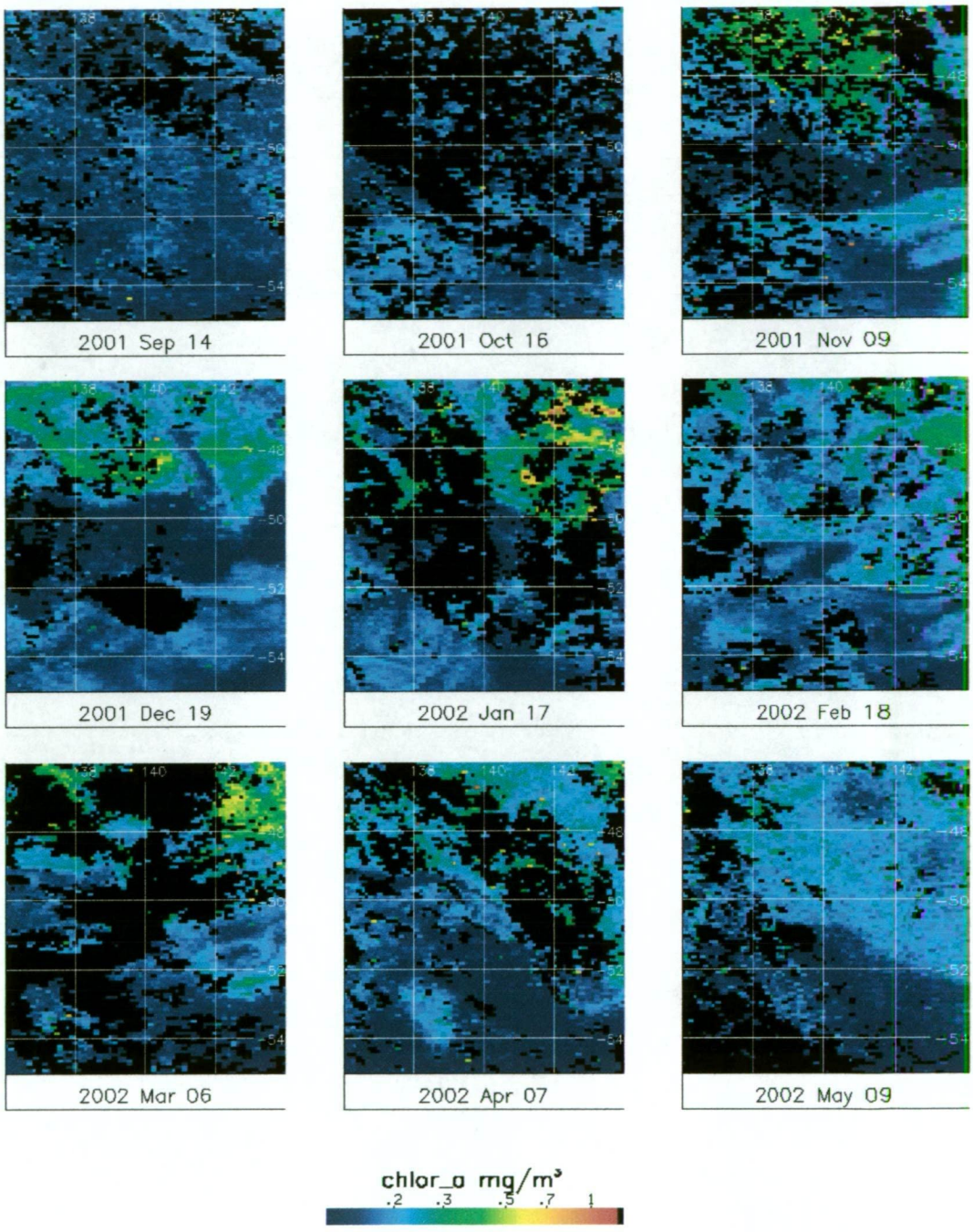


Figure 6.4. NASA SeaWiFS mapped composites of surface chlorophyll *a* biomass ($mg.m^{-3}$) for the region 136° to 144°E and 46°S to 56°S (approximately 9 km resolution), at approximately monthly intervals from September 2001 and May 2002. All SeaWiFS data are freely available from the following web-site: http://seawifs.gsfc.nasa.gov/

characterised by the high frequency of occurrence of *Limacina* spp., *Calanus simillimus* and *Clausocalanus laticeps*. However, the separation of Clusters 1 and 2 at the 46.5% level of dissimilarity demonstrated that the latter two species were indicative of Cluster 1 and not Cluster 2, as were ostracods, *Clausocalanus brevipes*, *Neocalanus tonsus*, *Oithona frigida*, *Themisto gaudichaudii*, *Thysanoessa macrura / vicina*, *Euphausia vallentini,* chaetognaths and *Rhincalanus gigas*. Cluster 2 samples occurred predominantly south of the SAF-N, and included a large number of December samples. Cluster 1 included samples from all months of the survey, principally occurring south of the SAF-N. Clusters 1 and 2 comprised 55% and 24% of samples respectively, and therefore represented the two major community types in the night samples.

Six clusters were identified in the night samples using the Bray-Curtis dissimilarity measure (Figure 6.5b). Cluster 6, dominated by February samples south of 53.57°S, separated from Clusters 1 to 5 at the 68.4% level of dissimilarity. Cluster 6 had no IndVal indicator species, pointing to low occurrence and abundance of all taxa within these segments (Figure 6.6). Conversely, Clusters 1 to 5 had maximum IndVals for foraminiferans and *E. vallentini*. The high IndVals (≥ 90%) for foraminiferans, appendicularians, *C. citer* and *O. similis* demonstrated the major contribution that these taxa made to the communities of most samples. Cluster 5 comprised six samples from November, December and January transects, all located south of the SAF-N and characterised by maximum IndVal for *Metridia* spp., while Clusters 1 to 4 had maximum IndVal for appendicularians (> 96%). Cluster 4 separated from Clusters 1 to 3 at the 53.23 % level of dissimilarity, was dominated by March samples north of the SAF-N, and had maximum IndVal for *P. borealis*. Clusters 1 to 3 had maximum IndVals for *O. similis* (~ 95%) and *R. gigas*, and values > 85% for appendicularians, *C. citer* and *Limacina* spp.. Cluster 3 included the northernmost January samples and was therefore similar to Cluster 4 of the Presence / Absence analysis (Figure 6.5a), but excluded March samples. The taxa with maximum IndVals for Cluster 3 were similar to those identified by 2ΔI for Cluster 4 of the Presence / Absence analysis, but included *Tomopteris* spp., chaetognaths, *Calocalanus* sp., *Thysanoessa macrura / vicina* and *Eucalanus* sp. Clusters 1 and 2 comprised 35% and 27% of samples respectively and had a similar sample composition to Clusters 1 and 2 of the Presence / Absence analysis. Together, Clusters 1 and 2 had maximum IndVals for *C. citer* and *Limacina* spp.

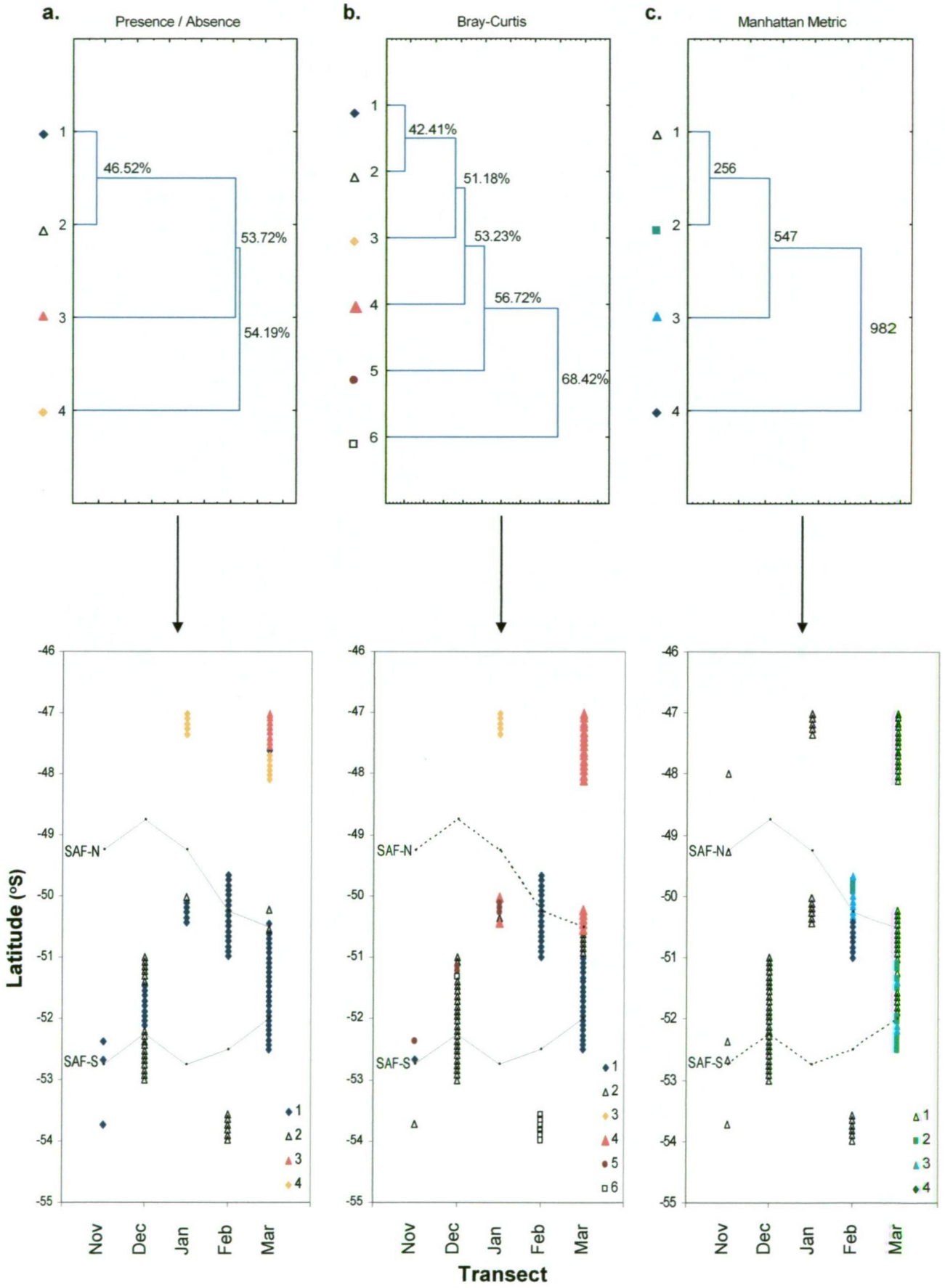


Figure 6.5. *legend overleaf...*

Figure 6.5. Cluster analysis of **night** samples by Un-Weighted Pair Group Average linkage using **a.** Sorensen's coefficient (Presence / Absence); **b.** $\log_{10}(x+1)$ abundance data and the Bray-Curtis dissimilarity measure **c.** raw abundance data (individuals.m^{-3}) for taxa occurring in $\geq$ 20% of samples and the Manhattan Metric. The upper panel indicates the clusters identified and their level of separation, and the lower panel indicates the spatial and temporal distribution of samples comprising each cluster.

Table 6.2. Frequency of occurrence of indicator taxa in cluster pairs determined by Presence / Absence analysis of **night** samples (Figure 6.5a). Indicator taxa (in **bold**) were identified by the Information Statistic - 2ΔI (Field et al. 1982). As 2ΔI has an approximate chi-square distribution indicator species were selected based on the 1% and 5% probability levels, corresponding with $2\Delta I_i > 6.635$ and $2\Delta I_i > 3.841$ respectively. Taxa above the space had $2\Delta I > 6.63$ and taxa below the space had $2\Delta I > 3.84$.

	Cluster 1 to 3 (n=95)	**Cluster 4 (n=11)**		**Cluster 1 (n=61)**	**Cluster 2 (n=26)**
Ctenocalanus citer	**89**	4	Ostracoda	**33**	1
Paracalanus sp.	0	**5**	*Calanus simillimus*	**50**	0
Sapphirina sp.	1	**7**	*Clausocalanus brevipes*	**39**	1
Vibilia sp.	0	**4**	*Clausocalanus laticeps*	**43**	4
Thysanoessa gregaria	2	**5**	*Neocalanus tonsus*	**21**	0
Salpa thompsoni	3	**11**	*Oithona frigida*	**26**	0
			Themisto gaudichaudii	**32**	2
Euchaeta sp.	0	**2**	*Thysanoessa mac / vic*	**48**	9
Hyperia sp.	0	**2**	*Euphausia vallentini*	**23**	0
Dairella latissima	0	**2**	Chaetognatha	**48**	5
Platysceloidea	0	**4**			
Euphausia longirostris	7	**5**	*Rhincalanus gigas*	**30**	3
	Cluster 1 to 2 (n=87)	**Cluster 3 (n=8)**			
Limacina spp.	**70**	1			
Calocalanus sp.	7	**4**			
Heterorhabdus sp.	0	**3**			
Metridia spp.	21	**8**			
Pleuromamma borealis	1	**7**			
Calanus simillimus	**50**	0			
Clausocalanus laticeps	**47**	0			
Hyperid sp.	3	**4**			
Euphausia longirostris	3	**4**			
Decapod	0	**2**			

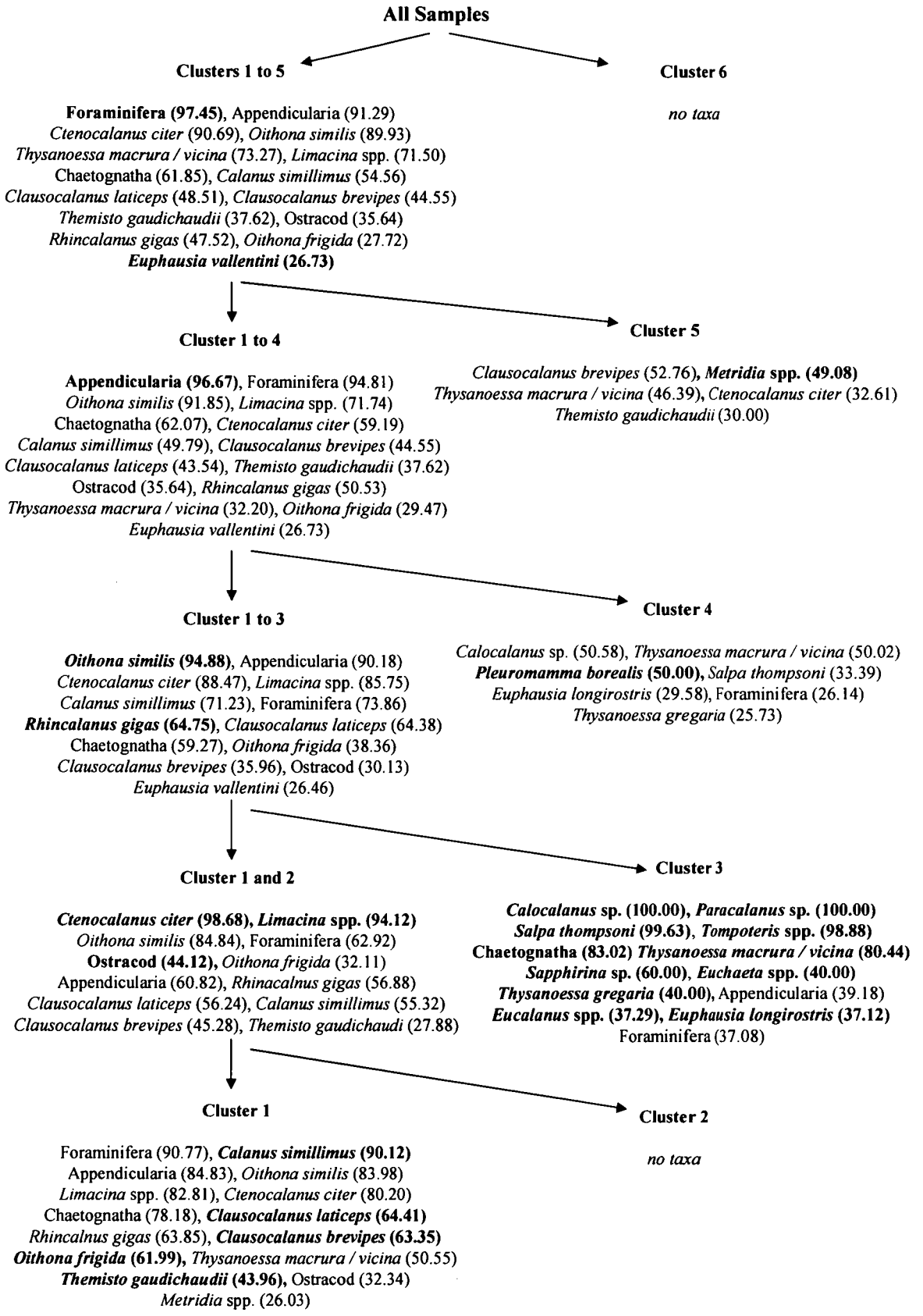


Figure 6.6. *legend overleaf...*

Figure 6.6. Night indicator taxa identified by applying Dufrene and Legendre's (1997) technique to clusters obtained using the Bray-Curtis dissimilarity measure and Un-Weighted Pair Group Average linkage. Taxa indicated for each sample grouping had indicator values ≥ 25%, which meant that they were present in at least 50% of samples in a group and that their relative abundance in that group was at least 50%. Maximum indicator values are in bold.

(both exceeding 94%), and ostracods. Cluster 2 was dominated by December samples south of 51°S and had no IndVal indicator taxa, while Cluster 1 was dominated by February and March samples south of the SAF-N and had maximum IndVals for *C. simillimus*, *C. laticeps*, *C. brevipes*, *O. frigida* and *T. gaudichaudii*.

Seventeen taxa remained in the night data set after being reduced to taxa occurring in ≥ 20% of samples. Using the Manhattan Metric four sample clusters were identified within this data sub-set (Figure 6.5c). Cluster 4 comprised February samples from between 50.41°S and 50.99°S (south of the SAF-N), and in comparison to Clusters 1 to 3 had significantly higher abundance levels of *Limacina* spp., *C. brevipes*, *C. citer*, *O. similis*, *R. gigas*, chaetognaths and appendicularians (Table 6.3). Cluster 3 comprised February samples between 50.33°S and 49.66°S, but also included three March samples south of the SAF-N, two of which were at the SAF-S. *Themisto gaudichaudii* occurred at significantly higher abundance levels within Cluster 3. Cluster 2 comprised February samples between 49.83°S and 49.91°S, and March samples south of 51°S. Both foraminiferans and *C. laticeps* showed no significant difference in abundance levels between Clusters 2, 3 and 4, but occurred at comparatively low levels in Cluster 1. *Calanus simillimus* occurred at significantly higher abundance within Clusters 2 and 3, while *O. frigida* was significantly more abundant within Clusters 3 and 4. Cluster 1 included all of the November, December and January samples, the most southerly February samples, and the majority of March samples. Cluster 1 was characterised by low abundance levels of all taxa, with only ostracods and *Thysanoessa macrura / vicina* densities not differing significantly from levels in any other cluster.

Samples in the Correspondence Analysis were generally closely clustered (Figure 6.7). However, two main groupings were discernable which largely reflected the results of the cluster analyses. The first grouping, comprised samples on the negative side of the x-axis, including the majority of December and February samples, and two November samples, and they were characterised by a high proportion of *C. citer*, *O. similis*, *O. frigida*, *R. gigas*, *Limacina* spp. and appendicularians. The second grouping comprised samples on the positive side of the x-axis, including all of the January and March samples, and the remaining November, December and February samples. This second grouping was characterised by a high proportional contribution of the copepods *Metridia* spp., *N. tonsus*, *C. simillimus*, *C. brevipes* and *C. laticeps*, the euphausiids *E. vallentini* and

Table 6.3. Average abundance (individuals.m^{-3}) of zooplankton taxa, occurring in ≥ 20% of **night** samples, for the four clusters identified using the Manhattan Metric (Figure 6.5c). Differences between clusters were investigated using ANOVA, performed on $\log_{10}(x+1)$ transformed abundance levels. Significance levels are indicated by F and p. Newman-Keuls multiple range tests were run to identify inter-cluster difference in species abundance levels. Significantly higher abundance levels are in bold and underlined. *** $p < 0.0001$.

Taxon	Cluster 1 (n=80)	Cluster 2 (n=13)	Cluster 3 (n=9)	Cluster 4 (n=8)	F	p
Foraminifera	37.42	**184.45**	**395.38**	**393.18**	43.34	***
***Limacina* spp.**	2.77	21.54	18.13	**64.15**	44.54	***
Ostracoda	0.43	0.54	0.31	0.59		
Calanus simillimus	1.08	**19.22**	**12.23**	4.12	43.93	***
Clausocalanus brevipes	0.75	1.34	1.19	**3.36**	9.56	***
Clausocalanus laticeps	0.39	**2.32**	**2.24**	**2.76**	21.53	***
Ctenocalanus citer	8.64	27.87	20.22	**118.24**	23.51	***
***Metridia* spp.**	0.39	0.33	0.24	0.42		
Neocalanus tonsus	0.60	0.48	0.37	0.08		
Oithona frigida	0.07	0.58	**4.21**	**5.51**	92.23	***
Oithona similis	7.13	12.75	68.57	**241.62**	59.01	***
Rhincalanus gigas	0.98	0.88	11.06	**43.86**	55.27	***
Themisto gaudichaudii	0.28	1.03	**1.61**	0.59	9.24	***
Thysanoessa mac / vic	2.03	1.84	0.78	1.42		
Euphausia vallentini	0.33	0.22	0.16	0.25		
Chaetognatha	1.35	1.82	4.21	**8.59**	20.23	***
Appendicularia	10.90	30.33	88.87	**223.19**	49.20	***

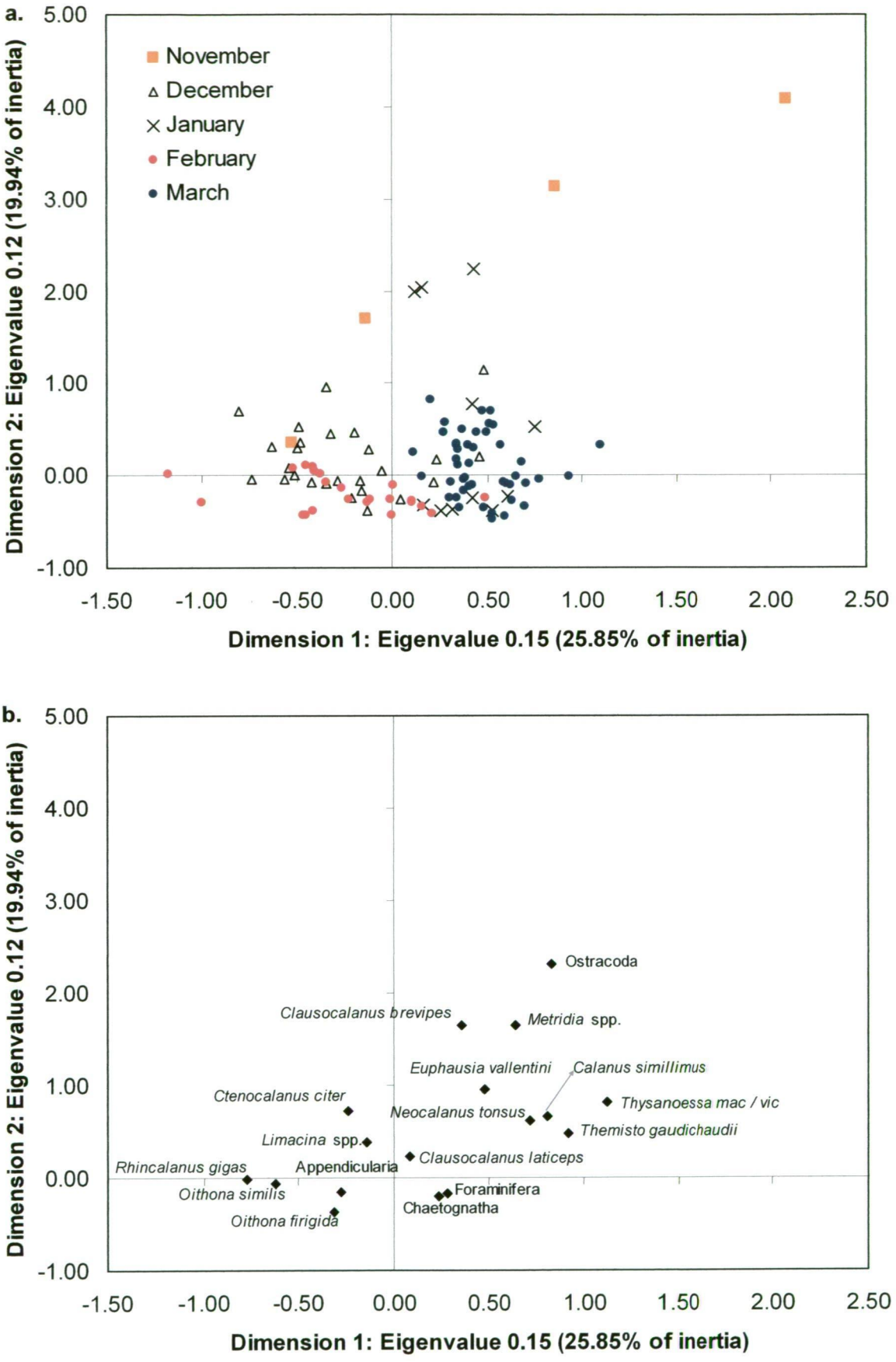


Figure 6.7. Ordination of **a.** samples and **b.** taxa using the first two dimensions of the Correspondence Analysis, based on taxa occurring in ≥ 20% of night samples.

T. macrura / vicina, *T. gaudichaudii*, foraminiferans, chaetognaths and ostracods. Two November samples had a particularly high proportion of ostracods.

6.3.4. Day Zooplankton Communities

Six clusters were identified from the Presence / Absence analysis of day samples (Figure 6.8a). Cluster 6 separated at the 56.8% level of dissimilarity and comprised samples north of the SAF-N from November, January and February. A large number of indicator species were identified using the 2ΔI, including *C. simillimus*, *Calocalanus* sp., *Eucalanus* sp., *Euchaeta* sp., *N. tonsus*, *Paracalanus* sp., hyperid sp., *T. gregaria*, *Thysanoessa macrura / vicina*, chaetognaths, *Salpa thompsoni*, hydromedusae, siphonophores, *Metridia* spp. and *E. vallentini* (Table 6.4). Clusters 3, 4 and 5 comprised small groups of generally widely spaced samples. Cluster 5 was characterised by the absence of *O. similis*. Cluster 4 comprised December / January samples from south of the SAF-N, and February / March samples north of the SAF-N, and was characterised by high frequencies of chaetognaths, *N. tonsus* and hydromedusae, and a low frequency of *Limacina* spp.. Cluster 3 comprised six December and January samples south of the SAF-N and had a low occurrence of *O. similis*, while *Thysanoessa macrura / vicina*, *T. gaudichaudii* and ostracods were relatively common. Cluster 2 (106 samples) included the majority of December to March samples, north and south of the SAF-N, indicating a high degree of similarity in the species composition of day samples. Cluster 1 (45 samples) was dominated by January samples south of 53.45°S and February samples between 49.08°S and 49.58°S. Cluster 1 and 2 were separated by the frequency of occurrence of *C. simillimus*, *C. citer*, *C. laticeps*, *C. brevipes*, *O. frigida*, *R. gigas*, *Thysanoessa* spp., chaetognaths, ostracods and *Primno macropa*. Cluster 2, comprising 51% of samples, was characterised by low frequencies of these taxa, while Cluster 1, comprising 22% of samples, was characterised by high frequencies.

Six sample clusters were identified using the Bray-Curtis dissimilarity matrix (Figure 6.8b). Less scatter of within cluster samples was evident than the Presence / Absence analysis (Figure 6.8a). Cluster 6 separated at the 70.4% level of dissimilarity and comprised five samples from November and December located south of the SAF-N and characterised by maximum IndVal for *Metridia* spp. (Figure 6.9). Cluster 1 to 5 had maximum IndVal for appendicularians and IndVals > 85%

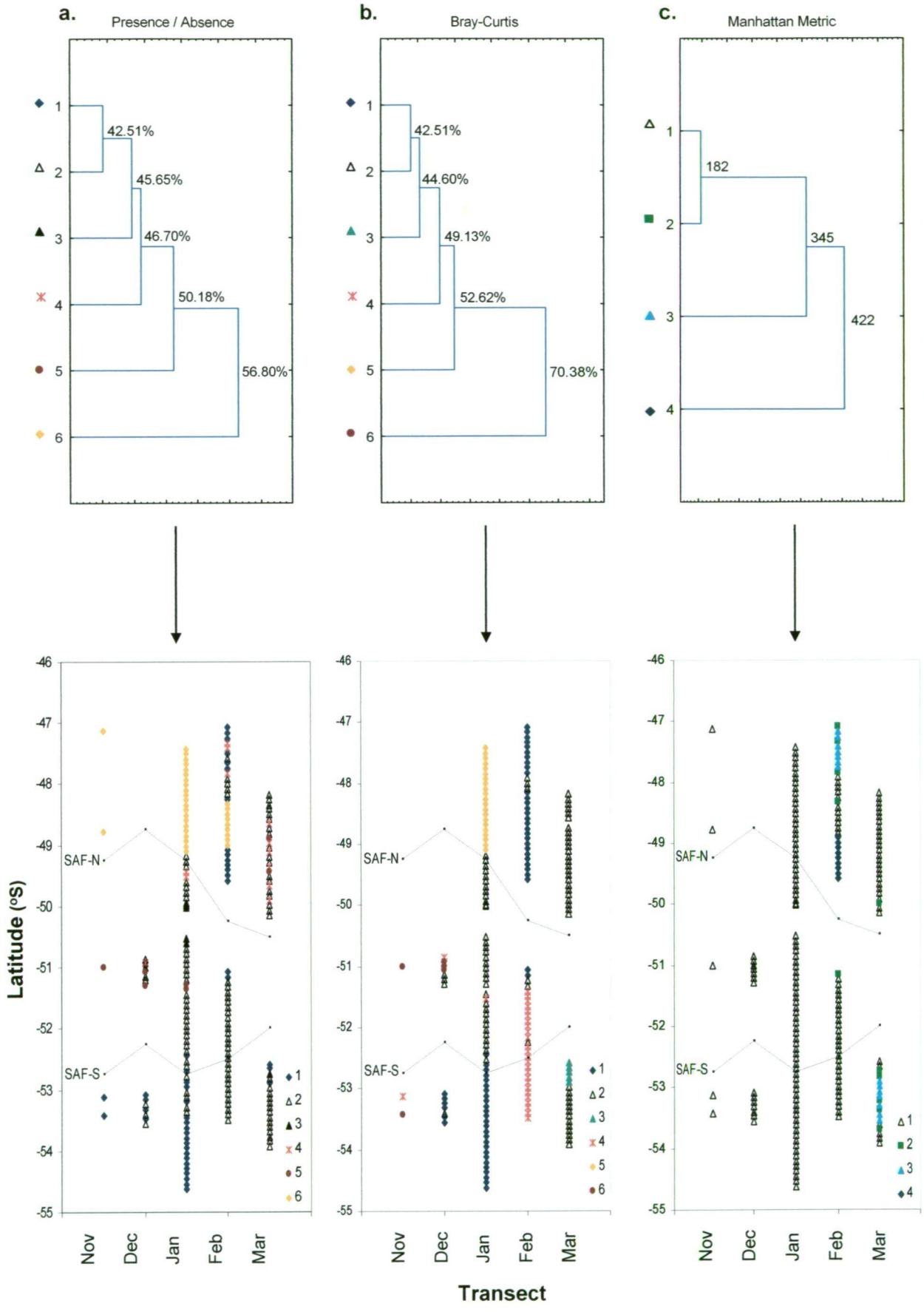


Figure 6.8. *legend overleaf...*

Figure 6.8. Cluster analysis of day samples by Un-Weighted Pair Group Average linkage using **a.** Sorensen's coefficient (Presence / Absence); **b.** $\log_{10}(x+1)$ abundance data and the Bray-Curtis dissimilarity measure **c.** raw abundance data (individuals.m^{-3}) for taxa occurring in $\geq$ 20% of samples and the Manhattan Metric. The upper panel indicates the clusters identified and their level of separation, and the lower panel indicates the spatial and temporal distribution of samples comprising each cluster.

Table 6.4. Frequency of occurrence of indicator taxa in cluster pairs determined by Presence / Absence analysis of **day** samples (Figure 6.8a). Indicator taxa (in **bold**) were identified by the Information Statistic - 2ΔI (Field et al. 1982). As 2ΔI has an approximate chi-square distribution indicator species were selected based on the 1% and 5% probability levels, corresponding with $2\Delta I_i > 6.635$ and $2\Delta I_i > 3.841$ respectively. Taxa above the space had $2\Delta I > 6.63$ and taxa below the space had $2\Delta I > 3.84$.

	Cluster 1 to 5 (n=176)	Cluster 6 (n=32)
Tomopteris spp.	11	**15**
Calanus simillimus	31	**17**
Calocalanus sp.	24	**21**
Eucalanus sp.	2	**16**
Euchaeta sp.	2	**11**
Neocalanus tonsus	9	**24**
Paracalanus sp.	0	**20**
Hyperid sp.	2	**13**
Thysanoessa gregaria	2	**7**
Thysanoessa spp.	78	**28**
Euphausia longirostris	1	**6**
Chaetognatha	47	**31**
Salpa thompsoni	3	**15**
Hydromedusae	8	**9**
Siphonophore	4	**7**
Metridia spp.	3	**5**
Euphausia vallentini	7	**7**

	Cluster 1 to 4 (n=169)	Cluster 5 (n=7)
Oithona similis	**160**	0

	Cluster 1 to 3 (n=157)	Cluster 4 (n=12)
Chaetognatha	35	**12**
Neocalanus tonsus	5	**4**
Hydromedusae	4	**4**
Limacina spp.	**100**	1

	Cluster 1 to 2 (n=151)	Cluster 3 (n=6)
Oithona similis	**149**	2
Thysanoessa spp.	67	**6**
Themisto gaudichaudii	21	**5**
Ostracoda	11	**4**

	Cluster 1 (n=45)	Cluster 2 (n=106)
Calanus simillimus	**21**	6
Clausocalanus brevipes	**27**	5
Clausocalanus laticeps	**23**	2
Ctenocalanus citer	**43**	45
Oithona frigida	**13**	1
Rhincalanus gigas	**29**	10
Thysanoessa mac / vic	**31**	36
Chaetognatha	**25**	10
Ostracoda	**8**	3
Primno macropa	**4**	0

for foraminiferans and *O. similis*, indicating the importance of these taxa to the communities of most samples. Cluster 5 separated from Clusters 1 to 4 at the 52.6 % level of dissimilarity and comprised the January samples north of the SAF-N, and was therefore similar to Cluster 6 of the Presence / Absence analysis (Figure 6.8a). A large number of IndVal indicator species were identified in Cluster 5 and these demonstrated considerable overlap with the 2ΔI indicator species identified for Cluster 6 of the of the Presence / Absence analysis (Figure 6.9, Table 6.4). No taxa had maximum IndVals for the combined samples of Clusters 1 to 4. Cluster 4 largely comprised February samples south of 51.40°S. Most taxa demonstrated low frequency of occurrence and abundance within this cluster, with only *O. similis* having IndVal exceeding 25%. Clusters 1 to 3 had maximum IndVal for foraminiferans. Cluster 3 comprised five samples between 52.59°S and 52.90°S and had maximum IndVals for *Calanus simillimus*, *Limacina* spp., *P. macropa* and hydromedusae. Clusters 1 and 2 comprised 30% and 39% of day samples respectively and were similar to Clusters 1 and 2 of the Presence / Absence analysis (Figure 6.8a). Cluster 2 largely comprised January samples from between the SAF-N and SAF-S and March samples north of the SAF-N, and had no taxa with maximum IndVal. Cluster 1 was dominated by January samples south of the SAF-S and February samples north of the SAF-N, and had maximum IndVals for *O. similis*, *C. citer*, *R. gigas*, *C. brevipes* and *C. laticeps*.

Reduction of the day data set to taxa occurring in ≥ 20% of samples produced a matrix with twelve taxa. Four sample clusters were identified from this matrix after application of the Manhattan Metric (Figure 6.8c). Cluster 4 comprised February samples north of the SAF-N, between 48.91°S and 49.58°S. *Clausocalanus brevipes*, *C. citer*, *O. similis*, *T. gaudichaudii*, chaetognaths and appendicularians all occurred at significantly higher abundance within Cluster 4 (Table 6.5). Cluster 3 comprised February samples north of 47.75°S and March samples located between 52.90°S and 53.53°S. Cluster 2 comprised eleven samples from February and March which were characterised by significantly higher abundance levels of *C. simillimus*. Cluster 2 samples were widely spaced, and distributes largely to the north of the SAF-N in February and to the south of the SAF-N in March. Cluster 1 comprised the remaining 173 samples, including all November, December and January samples, and the majority of the February and March samples. Foraminiferans and *Limacina* spp. both occurred at significantly higher abundance within Clusters 2, 3 and 4 than within Cluster 1.

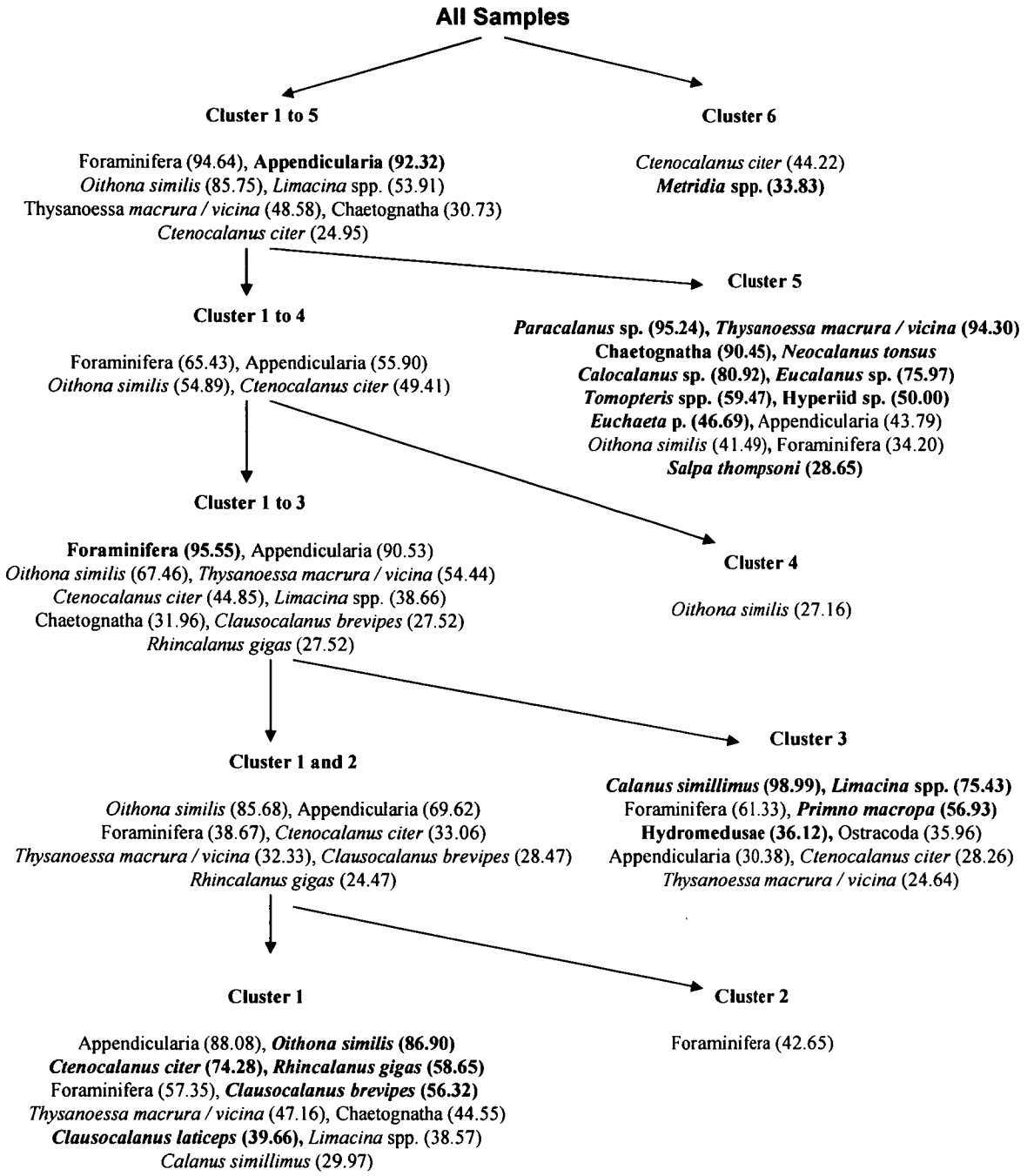


Figure 6.9. Day indicator taxa identified by applying Dufrene and Legendre's (1997) technique to clusters obtained using the Bray-Curtis dissimilarity measure and Un-Weighted Pair Group Average linkage. Taxa indicated for each sample grouping had indicator values ≥ 25%, which meant that they were present in at least 50% of samples in a group and that their relative abundance in that group was at least 50%. Maximum indicator values are in bold.

Table 6.5. Average abundance (individuals.m^{-3}) of zooplankton taxa, occurring in ≥ 20% of **day** samples, for the four clusters identified using the Manhattan Metric (Figure 6.8c). Differences between clusters were investigated using ANOVA, performed on $\log_{10}(x+1)$ transformed abundance levels. Significance levels are indicated by F and p. Newman-Keuls multiple range tests were run to identify inter-cluster difference in species abundance levels. Significantly higher abundance levels are in bold and underlined. * $p < 0.01$, *** $p < 0.0001$

Taxon	Cluster 1 (n=173)	Cluster 2 (n=11)	Cluster 3 (n=14)	Cluster 4 (n=9)	F	p
Foraminifera	38.39	**166.70**	**338.00**	**205.25**	43.49	***
***Limacina* spp.**	0.99	**4.05**	**2.61**	**4.50**	16.35	***
Calanus simillimus	0.61	**10.32**	1.80	4.47	14.69	***
***Calocalanus* sp.**	0.44	0.32	0.14	0.00		
Clausocalanus brevipes	0.24	0.19	0.57	**4.08**	22.46	***
Ctenocalanus citer	1.51	1.86	0.77	**10.90**	8.20	***
Oithona similis	8.52	10.25	12.57	**48.99**	14.58	***
Rhincalanus gigas	0.84	0.42	0.05	0.07		
Themisto gaudichaudii	0.16	0.13	0.00	**0.89**	8.10	***
***Thysanoessa* spp.**	1.81	0.99	1.05	1.20		
Chaetognatha	0.62	1.15	1.01	**1.48**	4.31	*
Appendicularia	11.30	23.80	38.89	**208.65**	46.63	***

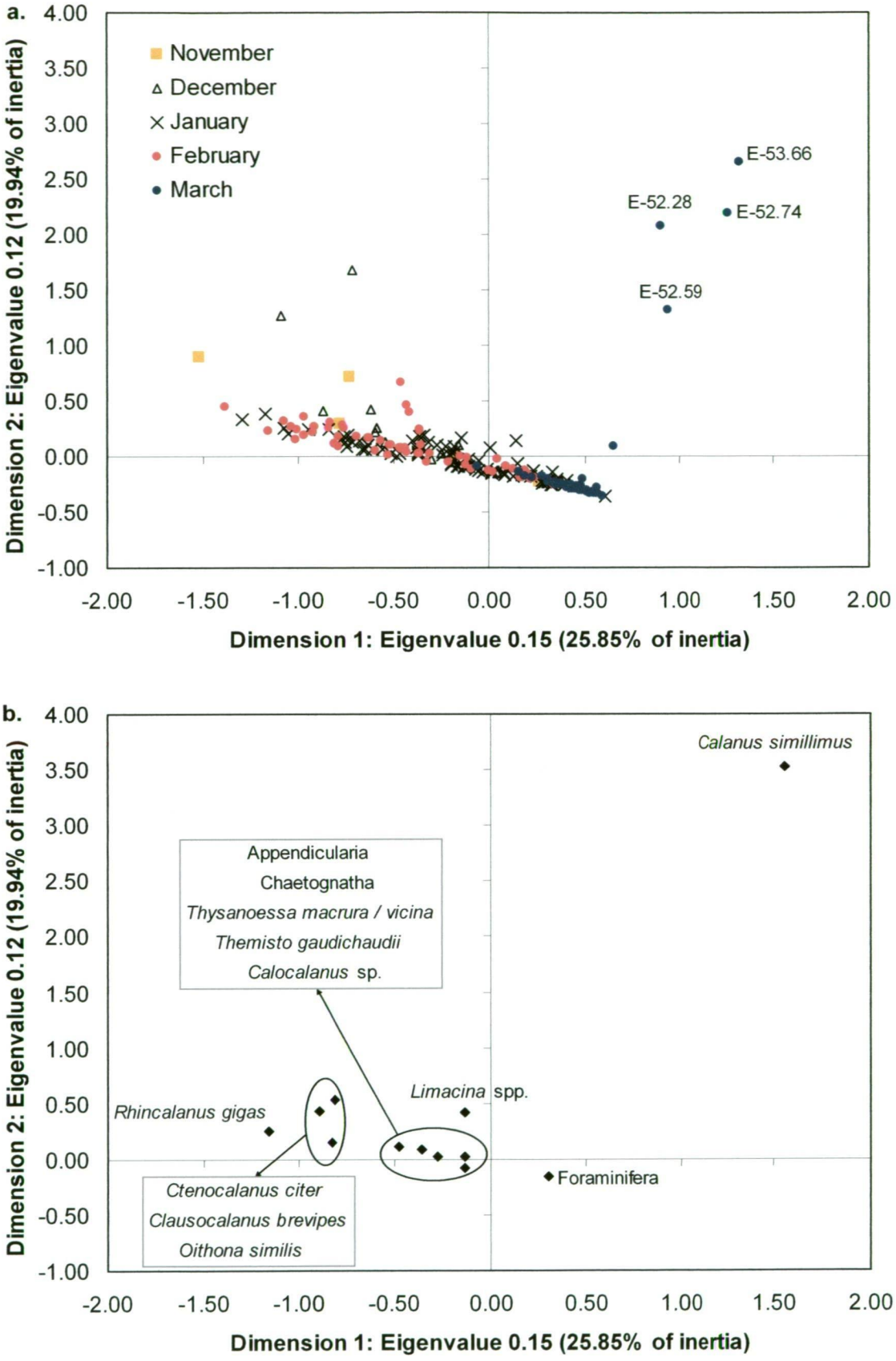


Figure 6.10. Ordination of **a.** samples and **b.** taxa using the first two dimensions of the Correspondence Analysis, based on taxa occurring in ≥ 20% of **day** samples.

Ordination of the first two dimensions of the Correspondence Analysis demonstrated that the majority of community variation occurred in the first dimension (Figure 6.10). There was a strong separation between samples characterised by a high proportional contribution of foraminifera (on the positive side of the x-axis) and samples characterised by a high contribution of other taxa (on the negative side of the x-axis). The majority of March samples fell within the former group, although, four samples from between 53.66°S and 52.28°S were characterised by a high contribution of *C. simillimus*. The important role of *C. simillimus* in these samples was demonstrated by the cluster analysis. The majority of November to February samples fell on the negative side of the x-axis, and were characterised by varying contributions of *R. gigas, C. citer, O. similis, C. brevipes*, appendicularians, chaetognaths, *T. macrura / vicina, T. gaudichaudii*, and *Calocalanus* sp.

6.3.5. Seasonal Zooplankton Abundance

Due to the necessary sub-division of samples into night and day, further sub-division by zone would have resulted in some regional groupings having a small sample size. Densities of the major zooplankton taxa were therefore averaged by transect for Figure 6.11. This had the effect of integrating biogeographic variation and small-scale patchiness, but provided an overall picture of the temporal density pattern. Zooplankton abundance was extremely low in October, averaging < 15 ind.m^{-3}. Levels had increased by November (night average = 51.58 ind.m^{-3}), and subsequently continued to increase at a slow rate from December (night average = 81.68 ind.m^{-3}) to January (night average = 114.76 ind.m^{-3}). Average transect abundance peaked abruptly in February (night average = 634.44 ind.m^{-3}), and maintained relatively high densities in March (average = 192.95 ind.m^{-3}).

Foraminiferans, *O. similis*, appendicularians, *C. citer* and *Limacina* spp. were the major contributors to average transect abundance. The seasonal density distribution of these taxa closely followed that of Total Abundance, although *C. citer* densities declined from November to January before reaching a February peak. *Clausocalanus laticeps, R. gigas*, and the nauplii and C1-3 copepodite stages of *C. simillimus* and *N. tonsus* occurred at lower densities than the aforementioned taxa but demonstrated a similar seasonal cycle. *Neocalanus tonsus* had peak densities in November, due to a single sample north of the SAF-N with densities of 35.8 ind.m^{-3},

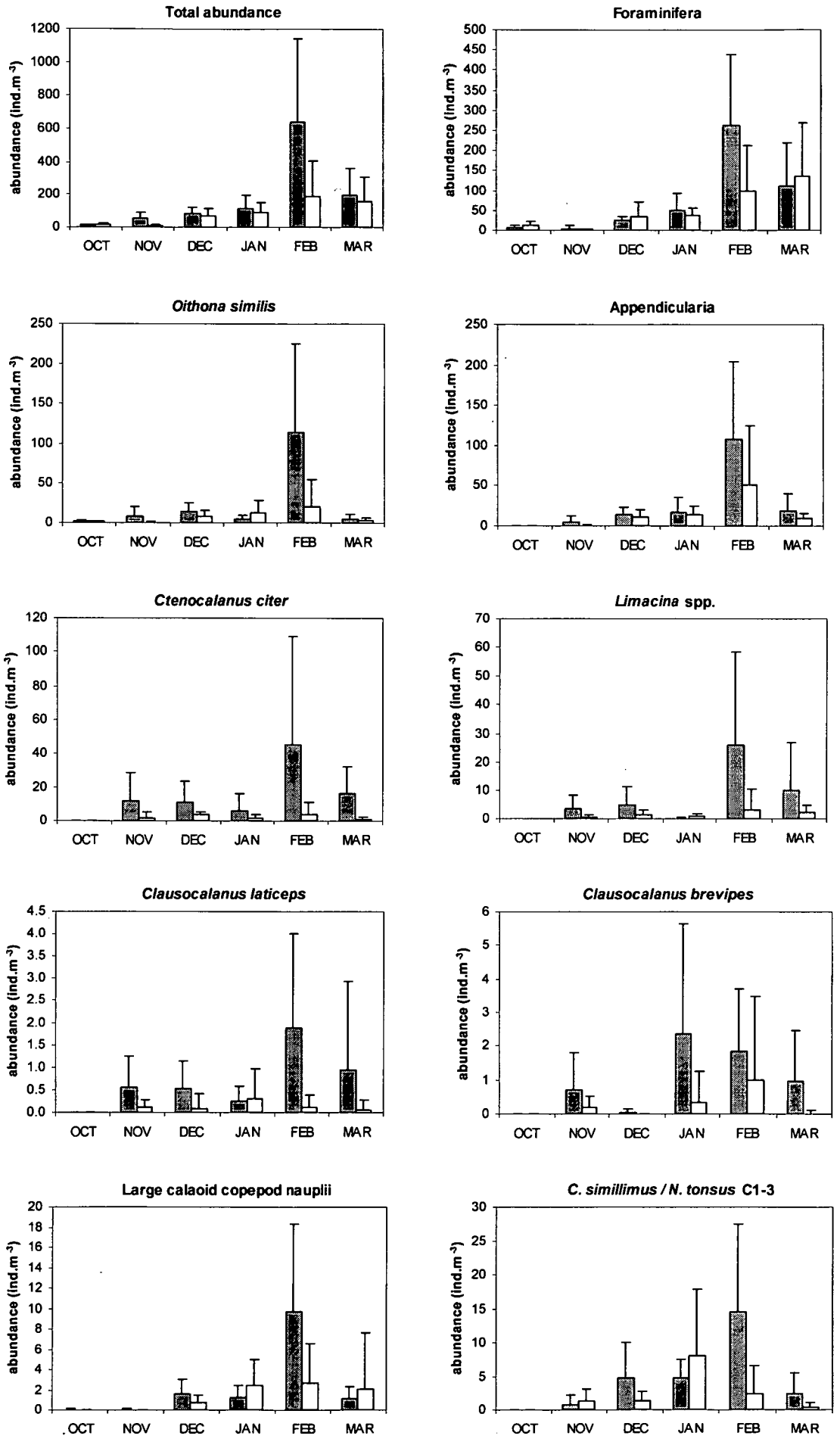


Figure 6.11. *continued overleaf...*

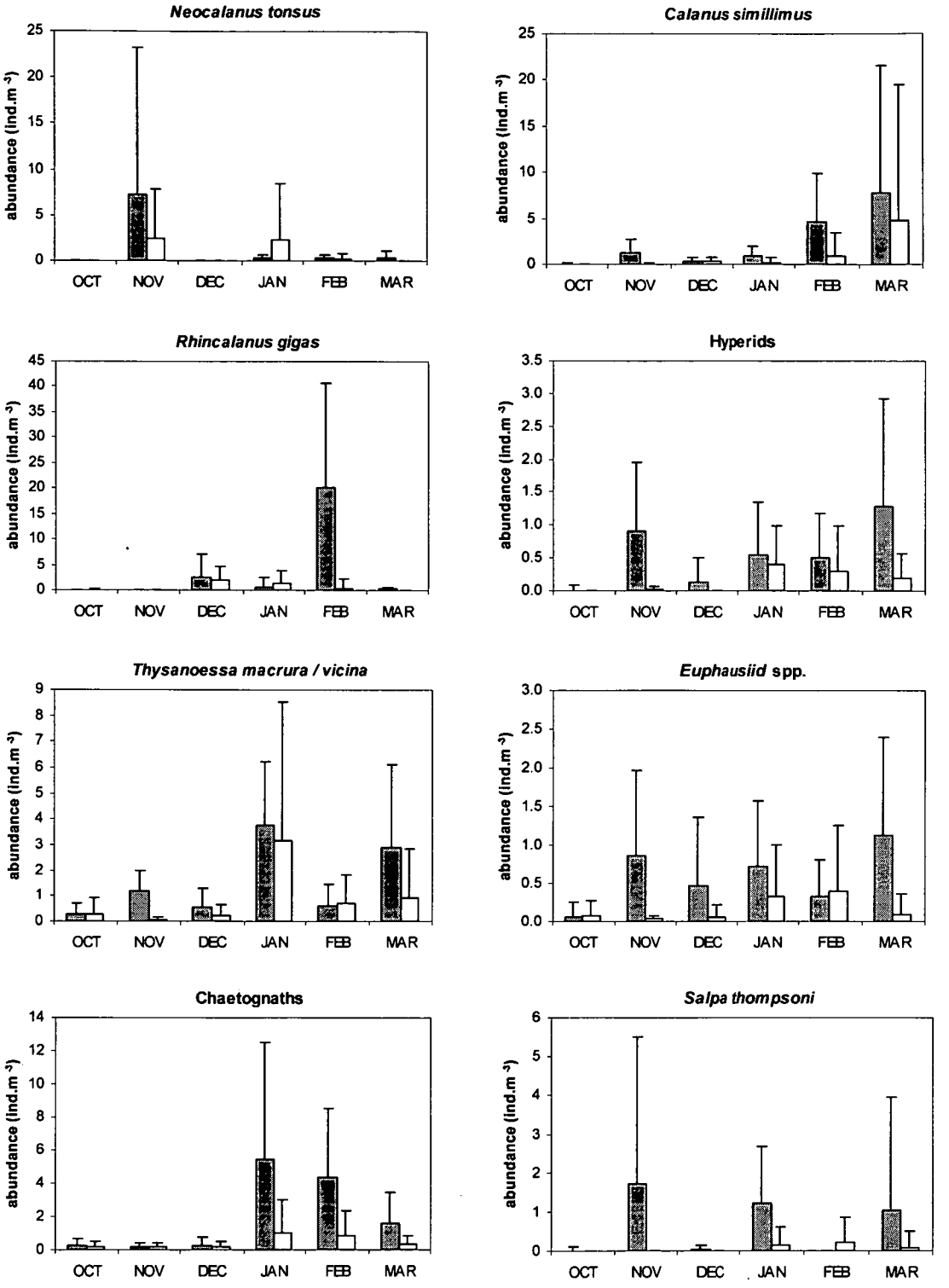


Figure 6.11. Average densities (individuals.m^{-3}) of major zooplankton taxa / groups for each of the six transects completed between October 2001 and March 2002. Dark bars illustrate night levels and open bars illustrate day levels.

and occurred at high densities in January when it was an important component of the SAZ community (Figure 6.9). *Calanus simillimus* had peak densities in March. Unlike *N. tonsus* this species was widely distributed through the study area, but occurred predominantly north of the SAF-N in February and south of the SAF-N in March (Figure 6.5c and 6.8c). *Clausocalanus brevipes*, chaetognaths and *T. macrura / vicina* had peak densities in January although the density distribution of the latter species did not have a strong seasonal pattern. Hyperiids, *Euphausia* spp. and *S. thompsoni* maintained relatively constant densities throughout the survey. *Salpa thompsoni* occurred predominantly in the SAZ (Figure 6.6 and 6.9). With few exceptions night abundance levels were substantially higher than day-time levels reflecting the strong diel vertical migration of most taxa. With the exception of February, foraminiferans showed similar densities during the night and day. In January the densities of calanoid copepodites C1-3 and *N. tonsus* were higher during the day than at night.

6.4. Discussion

6.4.1. Study Area

Along the 140°E meridian the latitudes 47°S to 55°S demarcate an oceanographically dynamic region, bisected by the northern and southern branches of the Sub-Antarctic Front (SAF-N and SAF-F), and the northern branch of the Polar Front (PF-N). On each transect during this study the SAF-N was associated with the steepest gradients in SST and SS, and multi-year altimetry data has shown that this front is the main current jet along 140°E (Sokolov and Rintoul 2002). The locations of all three fronts varied substantially between months, with the SAF-S ultimately moving southwards through the season. Positional fluctuations of the SAF and PF are characteristic throughout the Southern Ocean (Belkin and Gordon 1995, Nowlin and Klinck 1986, Orsi et al. 1995), and in the study area are reflected by a high degree of current variability (Sokolov and Rintoul 2002). Low amplitude seasonal warming of the surface waters begins in October and peaks in late January / early February (Rintoul and Trull 2001). In this study the warming period appeared to peak on the February transect. Warming of the surface waters is concurrent with a shallowing of the mixed layer, from > 400m in winter to 50-70m in summer within

the SAZ, and from a ~ 130m winter maximum to ~ 75m in summer between the SAF-N and the PF (Rintoul and Trull 2001).

Coincident with the warming of the surface waters was an increase in surface chlorophyll *a* biomass in the SAZ between October and November. The extended period of "high" chlorophyll *a* biomass from November to January was in good agreement with observations from the 1997 / 1998 season (Rintoul and Trull 2001). In 1997 / 1998 a December peak in chlorophyll *a* biomass was also observed between the northern and southern branches of the SAF, the ISAFZ, reaching 0.3 $mg.m^{-3}$. However, during 2001 / 2002 average values remained consistently < 0.2 $mg.m^{-3}$ in both the ISAFZ and PFZ. Although patches of relatively high chlorophyll *a* biomass (0.5-0.6 $mg.m^{-3}$) occurred, surface chlorophyll *a* biomass averaged < 0.3 $mg.m^{-3}$ throughout the survey highlighting the HNLC character of the study area. A subsurface chlorophyll maximum (SCM) has frequently been observed in the study area at 30-150m depth, particularly in the ISAFZ and PFZ (Yamaguchi and Shibata 1982, Kopczynska et al. 2001, Parslow et al. 2001). The SCM has been shown to develop in spring / early summer, when it may contribute 30-50% to total water column production, and to persist to late summer, although decreasing to < 20% column production (Parslow et al. 2001). Higher chlorophyll *a* biomass may therefore have existed deeper in the water column, and this may have been particularly important to zooplankton communities within the ISAFZ / PFZ, where surface levels were low.

6.4.2. Spatial Variation of Community Structure

Chapter 4 demonstrated that the SAF-N was the strongest biogeographic boundary along 140°E, and that the SAZ, although having many taxa in common with the communities to the south of the SAF-N, was characterised by a high frequency of Sub-Tropical and Temperate taxa. An ISAFZ community was identified between the northern and southern branches of the SAF, which, although influenced by SAZ waters, most closely resembled the community identified within the PFZ. The PF-N was a weak biogeographic barrier, and the PFZ formed part of an extensive, relatively homogenous zone extending southwards to the southern branch of the PF at ~ 59°S.

In this study both Presence / Absence analysis and the Bray-Curtis measure demonstrated that biogeographic separation of taxa to the north and south of the

SAF-N was a seasonally consistent feature, evident in both night and day samples but particularly in the former. A large number of Sub-Tropical and Temperate taxa were identified in the SAZ, including the copepods *Calocalanus* sp., *Eucalanus* sp., *Paracalanus* sp., *Pleuromamma borealis* and *Sapphirina* sp., the hyperiids *Dairella latissima* and Platysceloidea, and the euphausiids *Euphausia longirostris* and *Thysanoessa gregaria* (Gibbons 1997, Bradford-Grieve et al. 1999, Vinogradov 1999). *Salpa thompsoni* was also characteristic of the SAZ, occurring at high densities in this region and low densities to the south of the SAF-N, despite its wide Antarctic distribution (Casareto and Nemoto 1986, Chiba et al. 2001). Conversely, the ISAFZ and PFZ were not characterised by zonally unique taxa, and where community differences did coincide with the SAF-S they were due to variation in the frequencies and densities of a common taxonomic set.

In addition to the biogeographic separation of taxa across the SAF-N, a high degree of intra- and inter-zonal patchiness was evident in the spatial distribution of samples characterised by the same community structure. High resolution Optical Plankton Counter (OPC) sampling in the Atlantic Sector demonstrated a similar patchiness in SAZ and PFZ zooplankton which was strongly correlated with hydrographic features and small scale variation in phytoplankton densities (Read et al. 2002). Small-scale hydrographic variability was clearly evident in the distribution of SST and SS values along 140°E and a good example of intra-zonal physical patchiness influencing community structure was provided by the Presence / Absence analysis of night samples from the March transect. Here, two distinct communities were identified north of 48°S (Figure 6.5a) which were strongly associated with distinct water masses (Figure 6.2). A high degree of heterogeneity was also evident in the distribution of surface chlorophyll *a* biomass. Horizontal patchiness of zooplankton communities is likely to have been further influenced by differences in the vertical distribution of taxa due to variable light levels and water column variation in chlorophyll *a* biomass (e.g. the SCM).

Despite the occurrence of unique taxa in the SAZ, small-scale patchiness, and heterogeneity in community distribution, communities in all zones were dominated by a relatively small number of common taxa during both night and day. These taxa could broadly be divided into two groups, the first of which, the "Core Taxa", comprised foraminiferans, *Oithona similis* and appendicularians. The Core Taxa typically occurred at high frequencies and dominated total sample abundance (average = 75% of total abundance). The second group, the "Summer Taxa",

comprised the pteropod *Limacina* spp., the large calanoid copepods *Calanus simillimus* and *Rhincalanus gigas,* the small calanoid copepods *Clausocalanus brevipes*, *Clausocalanus laticeps* and *Ctenocalanus citer,* the cyclopoid copepod *Oithona frigida*, and chaetognaths. The Summer Taxa were not as ubiquitous as the Core Taxa, partly due to greater diel variation, but were widespread in the SAZ, ISAFZ and PFZ, and their densities reached high levels. As a consequence of their dominance, most of the communities identified during the study represented different iterations of the frequency distributions and relative densities of the Core and Summer Taxa.

6.4.3. Seasonal Community Succession

Over the noise of spatial variability a strong seasonal succession was evident in the zooplankton of the study area. Due to the dominance of community structure by Core and Summer Taxa, this succession was most clearly evident as a temporal change in zooplankton densities, rather than a fundamental change in species composition. In October (spring) surface zooplankton densities were low both to the north and south of the SAF-N. Densities were comparable to average winter levels recorded in the PFZ / IPFZ south of Australia (Hosie et al. 2003), and represented ~ 2% of average values recorded in February. Depth integrated sampling in the Atlantic sector of the Southern Ocean has shown winter copepod densities to be 24% of summer levels in the top 1000m of the water column (Atkinson and Sinclair 2000). In addition to seasonal density decline, many zooplankton undergo significant seasonal migrations (e.g. Schnack-Schiel and Mizdalski 1994, Atkinson 1998). By integrating the upper 1000m of the water column, Atkinson and Sinclair's (2000) study would have incorporated the majority of taxa despite seasonal migration out of the surface waters. The extremely low October densities recorded in this survey indicated that many taxa had not yet migrated back into the surface waters sampled by the CPR.

Zooplankton densities had increased by November and this was reflected by the abundance levels of most taxa. The region to the north of the SAF-N was characterised by high densities of *Salpa thompsoni* (up to 9 ind.m^{-3}), coinciding with the highest surface biomass of chlorophyll *a*. During night sampling on the November voyage chains of *S. thompsoni* were frequently observed at the sea surface in this region (personal observation). Average transect densities continued to

increase incrementally during December and January. No samples were collected north of the SAF-N in December, however Sub-Tropical and Temperate taxa were an important component of this region in January. In addition, *S. thompsoni* continued to maintain relatively high densities in the SAZ while remaining scarce in the ISAFZ and PFZ. Despite the variations in community structure identified by Presence / Absence analysis and the Bray-Curtis measure, as well as zonal separation of samples and chlorophyll *a* biomass remaining consistently low in the ISAFZ / PFZ, the Manhattan Metric demonstrated a high degree of sample similarity between November and January based on the absolute abundance levels of common taxa.

Average transect densities peaked abruptly in February. However, the Manhattan Metric demonstrated that high densities were not evenly distributed across the transect. The abrupt abundance peak was largely due to a small group of samples located in the vicinity of the SAF-N which were characterised by the highest survey densities of foraminiferans, *Limacina* spp., *C. citer*, *O. similis*, *R. gigas* and appendicularians. Average and maximum densities within these samples were 1197.95 ind.m^{-3} and 1740 ind.m^{-3}, respectively. Both the SAF and PF have been noted as regions of biological enhancement (Lutjeharms et al. 1985, Laubscher et al. 1993, Banse 1996, Bathmann et al. 1997, Dubischar et al. 2002). A combination of physical processes and behavioural patterns may have operated to concentrate zooplankton densities at the SAF-N (Franks 1992, Fransz and Gonzalez 1997, Read et al. 2002). February densities in the SAZ were high (average = 362.10 ind.m^{-3}), although substantially lower than levels recorded at the SAF-N. As at the SAF-N, densities in the SAZ were dominated by foraminiferans, *Limacina* spp., *C. citer*, *O. similis*, *R. gigas* and appendicularians, while *C. simillimus* was also abundant. The Manhattan Metric demonstrated a high degree of patchiness in the abundance levels of these taxa, reflecting small scale variation in their horizontal and / or vertical distributions. Little enhancement of zooplankton densities was observed in the ISAFZ and PFZ and average densities within these two zones was 27.58 ind.m^{-3}.

By March, average transect densities had decreased substantially from February levels. A large part of this decrease was due to the absence of the high density SAF-N community identified in February. Apart from a single sample with high densities of *C. simillimus* and foraminiferans, abundance levels were low at the SAF-N in March. Similarly, densities had declined throughout the SAZ, returning to

pre-February levels, although *S. thompsoni* reached 13.13 ind.m^{-3}. In contrast to the SAZ, densities to the south of the SAF-N had increased substantially (average = 268.19 ind.m^{-3}). As in the February SAZ community, high densities in the ISAFZ and PFZ were dominated by common Core and Summer Taxa. There was therefore a north to south shift in the distribution of the high abundance "peak communities". The predominant direction of transport of the ACC in the study area is eastwards, with a weak northward component in the surface waters due to Eckman drift (Rintoul and Trull 2001). The north to south shift in density distribution was therefore most likely to have been due to a latitudinal gradient in the timing of seasonal development across the study area (Voronina 1972). Densities recorded in the ISAFZ and PFZ in March were similar to levels recorded in the SAZ in February despite the latter region having consistently higher surface chlorophyll *a* biomass. It is possible that a Sub-Surface Chlorophyll Maximum (SCM) played a role in supporting zooplankton populations in these regions.

6.4.4. The influence of Population Cycles on seasonal succession

The seasonal cycles of many Southern Ocean zooplankton are strongly tied to the cycle of primary production, with reproduction occurring in spring so that the new generation can get maximum gain from the spring bloom, and have the longest possible growing season (Fransz 1988, Atkinson 1998). It is therefore noteworthy, and somewhat anomalous, that the highest zooplankton densities in this study occurred approximately three months after the spring increase in phytoplankton biomass. Population cycles (particularly stage structure) may have contributed significantly to this observed temporal density distribution. The highly abundant small copepods *O. similis* and *C. citer* both have reproductive peaks in early spring (Schnack-Schiel and Mizdalski 1994, Fransz and Gonzalez 1995, Atkinson 1998). Samples collected at the PFZ of the Atlantic sector using 100μm mesh demonstrated that the populations of these two species were dominated by C1 to C3 copepodite stages between December 6 and January 5 1995 / 1996 in the Atlantic sector (Dubischar et al. 2002). The 270μm mesh used in the present study has been calculated to collect 3.24% to 3.8% of adult *Oithona* spp. (Robertson 1968, Gallienne and Robins 2001). Considering that a mesh size approximately 75% of copepod width is required to catch 95% of all individuals of a given size (Nichols and Thompson 1991), and using the stage specific size measurements for *C. citer* of

Heron and Bowman (1971), only Adult and C5 *C. citer* would have been effectively sampled by 270μm mesh.

The densities recorded in December and January were therefore in all probability a substantial underestimate of total levels. The decline in abundance of *C. citer* observed from November to January may have reflected the decreasing abundance of the over-wintering population. Conversely, the high densities of *O. similis* and *C. citer* recorded in February and March were representative of their late summer populations being dominated by larger and therefore more effectively sampled stages. The rapid increase in the densities of chaetognaths recorded between December and January may have been indicative of the under-sampled copepod densities during this period. Although having life spans of a matter of weeks (Mucke and Hemleben 1999), foraminiferans demonstrated a similar temporal density distribution to small copepods. Sediment trap data from 1997 to 1999 demonstrated a seasonal change from a *Globigerina bulloides* / *Globorotalia inflata* dominated community in spring to a *Neogloboquadrina pachyderma* dominated community in late summer (King and Howard 2001). The latter species reaches a larger size than either *G. bulloides* or *G. inflata* (Mucke and Hemleben 1999), and so may have been more effectively sampled, although life history differences and vertical distributions may also have contributed. Seasonal size structure may also have contributed to the difference in the timing of density peaks between the Seasonal Ice Zone (SIZ) (Chapter 5) and the SAZ / ISAFZ / PFZ, notably the earlier peak in small copepod densities (particularly *O. similis* and *C. citer*) in the former region (Figure 5.10 and Figure 6.11). The SIZ samples were characterised by high numbers of diatoms, and their correspondence with high densities of small copepods indicates that their presence may have reduced the size of the 270μm mesh enabling it to more effectively sample these taxa at a stage in the season when small copepodite stages (C1 to C3) dominated.

In contrast to small copepods and foraminiferans, the larger community components, including *T. macrura / vicina*, *Euphausia* spp., hyperiids and *S. thompsoni* showed a more even temporal density distribution. However, the stage structure data for the large calanoid copepods *Calanus simillimus* and *Neocalanus tonsus* demonstrated a strong seasonal cycle (Figure 6.12), and this had a significant influence on the seasonal community succession. The November samples had high densities of C4 to Adult *C. simillimus* and *N. tonsus* relative to December and January levels, and these stages dominated population structure. These specimens

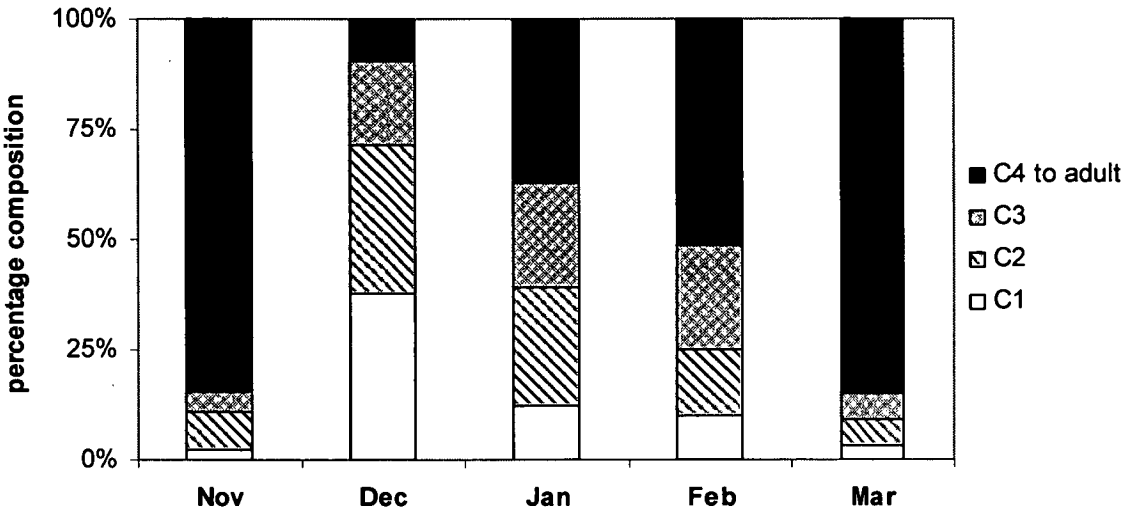


Figure 6.12. Stage structure of *Calanus simillimus* and *Neocalanus tonsus* for monthly transects completed between November 2001 and March 2002.

represented the over-wintering generation and, as Spring spawning has been shown to occur for both species, would have been dominated by reproductively mature adults (Voronina et al. 1978, Ohman et al. 1989, Atkinson 1991). The occurrence of relatively large numbers of calanoid nauplii in December, in comparison to November levels, probably reflected the remnants of this spawning event. The new generation, comprising C1 to C2 copepodites, dominated population structure in December, and the modal age shifted through the survey to C4 to Adult stages in March. The high contribution of *C. simillimus* to C4 to Adult specimens, and the low contribution made by *N. tonsus*, concurs with previous data on their seasonal cycles. Atkinson (1991) demonstrated peak densities of adult *C. simillimus* in the Scotia Sea in March, while Ohman et al. (1989) highlighted a seasonal migration of the majority of the *N. tonsus* population below 500m by late January. A notable peak in the densities of calanoid nauplii in February, coinciding with the high densities of *C. simillimus* C4 to Adults, supports the second, late summer spawning event for this species proposed by Atkinson (1991). Population changes were reflected by the community analysis with *C. simillimus* being an important community component, in terms of both frequencies and abundance levels, in February and March, while *N. tonsus* was an important component from November to January.

6.4.5. Implications

Using 100μm mesh Dubischar et al. (2002) recorded small copepod densities of up to 49 000 ind.m^{-3} within the PFZ in the Atlantic sector of the Southern Ocean in December and early January. These high densities were dominated by C1 to C3 copepodite stages of *O. similis*, and to a lesser extent *Ctenocalanus citer*. Correction of *O. similis* densities by averaging the sampling efficiencies of 270μm mesh calculated by Robertson (1968) and Gallienne and Robins (2001), gave densities of 1430 ind.m^{-3} for CPR densities of 50 ind.m^{-3}, and maximum *O. similis* densities of ~ 11 570 ind.m^{-3} at the SAF-N. These values do not include early copepodite stages and are therefore underestimates, particularly in December and January. *Oithona similis* has a daily carbon demand of ~ 100% of body carbon (Atkinson 1994). In the low chlorophyll Sub-Antarctic environment of the Atlantic sector *O. similis* has been shown to derive < 35% of body carbon from the phytoplankton (Atkinson 1996). The deficit appears to be made up by feeding on microheterotrophs and detrital matter, including faecal pellets (Atkinson 1996, Dubischar et al. 2002, Mayzaud et

al. 2002). Indeed, *Oithona* spp. has been shown to derive up to 30% of its daily carbon requirements by coprophagy (Gonzalez and Smetacek 1994). This may have been responsible for the very low faecal pellet concentrations recorded in the PFZ of the Atlantic sector (Dubischar and Bathmann 2002).

In the relative absence of large grazers (e.g. euphausiids), and given the low grazing impact of large calanoid copepods (Dubischar and Bathmann (1997) recorded a grazing impact of < 1% of daily primary production), and low diatom grazing but high recycling potential of *Oithona* spp. (Smetacek et al. 1990), direct sedimentation of diatoms is likely to be the major contributor to Particulate Organic Carbon (POC) flux in the PFZ / ISAFZ. Sediment trap data collected between spring and late summer of 1997 / 1998 along 140°E indicated that this was indeed the case, with biogenic silica making a high contribution to total mass flux in the PFZ (> 50%) (Trull et al. 2001a). However, POC flux recorded by Trull et al. (2001a) was three to seven times lower than in the Atlantic sector where a similar small copepod dominated community prevails (Dubischar et al. 2002). Diatom blooms with chlorophyll *a* biomass of up to 4 $mg.m^{-3}$ have been recorded in the PFZ in the Atlantic sector (Bathmann et al. 1997), and average values appear to be consistently higher than those south of Australia, between 90° and 145°E (Dubischar et al. 2002, Trull et al. 2001a, Moore and Abbott 2002). Although the data for the Australian sector were derived from surface measurements, even the maximum values measured for the SCM (1.6 $mg.m^{-3}$) are considerably lower than the maximum vales recorded in the Atlantic (Parslow et al. 2001). Given the similarities in zooplankton community structure between these two sectors, the differences in vertical flux would appear to be a reflection of low productivity in the Australian sector.

A significant result of the Trull et al.'s (2001a) sediment trap study along 140°E was the recording of POC flux in the SAZ equal to that in the PFZ despite a low contribution of diatoms to the phytoplankton community and vertical flux in this zone (Kopczynska et al. 2001, Sedwick et al. 2002). The large grazer *S. thompsoni* is considered to be an important zooplankton contributor to vertical flux (Smetacek et al. 1990, Dubischar and Bathmann 2002). *Salpa thompsoni* thrives in low phytoplankton concentrations (Chiba et al. 1998, Perissinotto and Pakhomov 1998), undertakes diel vertical migrations in the upper 200m of the water column (Casareto and Nemoto 1986), and produces large fast sinking faecal pellets (Bruland and Silver 1981). The high densities of *S. thompsoni* recorded north of the SAF-N during this study indicate that this species may have played an important role in POC flux

to the deep-sea floor during the 1997 / 1998 sediment trap study. Other potentially important contributors to biogeochemical cycling were appendicularians and the pteropod *Limacina* spp. (Honjo et al. 2000), both of which occurred at relatively high densities in this study.

6.4.6. Summary

This study provided the first detailed analysis of the seasonal cycle of zooplankton communities in the Sub-Antarctic to Polar Frontal zones of the Southern Ocean south of Australia. Despite strong biogeographic differences between the zones to the north and south of the SAF-N, the SAZ and ISAFZ / PFZ respectively, community structure in all zones was dominated by a suite of common taxa. These included the ubiquitous Core Taxa (foraminiferans, *Oithona similis*, appendicularians), and the Summer Taxa (*Calanus simillimus*, *Rhincalanus gigas, Ctenocalanus citer, Clausocalanus brevipes, Clausocalanus laticeps, Oithona frigida*, *Limacina* spp. and chaetognaths). Due to the dominance of the Core and Summer Taxa the seasonal cycle was most clearly evident as a temporal change in zooplankton densities, rather than a fundamental change in taxonomic composition. In October surface zooplankton densities were at winter levels, but increased rapidly by November. Subsequently densities increased slowly through to January. A rapid peak in densities was reached in the SAZ in February and in the ISAFZ / PFZ in March.

The long delay between the spring increase in phytoplankton densities and peak zooplankton densities was probably most strongly influenced by the inefficient sampling of the early life stages of small, high density taxa by the 270μm mesh used in this survey. However, seasonal changes in the vertical distribution of populations may have contributed. A similar succession was evident during both night and day, despite the influence of diel migration and the two data sets having different spatial coverage. Given the predominant eastward flow of the ACC and average inter-frontal current velocities of 5-7 $cm.s^{-1}$, the six transects conducted during this survey would have been broadly representative of the SAZ, ISAFZ and PFZ 350 to 490nm east and west of 140°E.

Finally, the high degree of seasonal variation observed in both Chapters 5 and 6 clearly demonstrated the necessity of these data for the analysis of long-term cycles. In Chapter 5 a shift in community structure was observed through the season

in the SIZ. An accumulation of inter-annual single transect (snapshot) studies could result in this seasonal change being perceived as long-term change. A change in community structure was not observed in the SAZ / ISAFZ / PFZ, however densities differed significantly through the season (Chapter 6). These seasonal data demonstrated that the low densities observed in the SAZ in the Chapter 4 single transect study were not the norm throughout the season, with higher densities being recorded one month previously.

Chapter 7

Conclusion

"*The researches of many commentators have already thrown much darkness on this subject, and it is probable that if they continue we shall soon know nothing at all about it.*"

- Mark Twain

This study was structured around the dual, intrinsically linked aims of quantifying the spatio-temporal distribution of zooplankton communities in the Southern Ocean south of Australia and providing a starting point for long-term monitoring, against which past and future variability can be measured. Prior to the inception of the Southern Ocean CPR Survey the only previous CPR sampling conducted in this ocean had been completed in 1925 in the Drake Passage using a prototype model (Hardy 1926). An essential component of this thesis was therefore quantification of the sampling characteristics of the Type II Mark V CPR (Chapter 3). With the majority of zooplankton sampling in the Southern Ocean having been completed using vertically or obliquely hauled nets, the calibration was achieved through direct comparison with vertically hauled NORPAC nets.

From a review of 113 documents pertaining to Southern Ocean plankton, Razouls et al. (2000) surmised that:

"*...our knowledge of pelagic biodiversity is gleaned from sampling during oceanographic surveys, which makes it discontinuous and dependent on available sampling gear.*"

- Razouls et al. (2000), page 343, paragraph 2

The low spatial and temporal resolution of data sets resulting from the coupling of zooplankton and oceanographic surveys, does not provide comprehensive sampling of zooplankton communities, and in addition, makes them inadequate for biogeographic studies (Section 4.1). Overall, Razouls et al. (2000) found a paucity of large-scale studies and an absence of quantitative data on species abundance levels. The CPR is less effective than traditional nets at quantifying

biodiversity, under-sampling many components of the zooplankton community. However, it has a major advantage in biogeographic studies, being able to sample rapidly, expansively, and at high resolution, while also integrating natural plankton patchiness (Section 1.2). The applicability of these characteristics to biogeographic studies was clearly demonstrated in Chapter 4. High speed sampling by the CPR enabled the collection of 5nm resolution samples over an unbroken 1171nm transect in a one week period. These data effectively provided a snapshot in time of the spatial distribution of zooplankton communities over an area spanning all but one of the major fronts in the Southern Ocean south of Australia. The differences between CPRs and traditional nets covered here highlight the value of the calibration study in providing a link between these two fundamentally different sampling systems. Specifically it enables the comparison of spatial ecology studies conducted using CPRs with historic and future biodiversity and / or species biology data collected using traditional nets.

The analysis of spatial variation of zooplankton communities from the 1171nm transect described above identified a high degree of zonal complexity south of Australia which was strongly correlated with the region's unique oceanographic environment (Chapter 4). The significant correlation between community structure and chlorophyll *a* biomass demonstrated that the relationship between the physical environment and zooplankton extended beyond purely that of direct physiological control to indirect control through its influence on phytoplankton communities and their production. A potentially important feature of the phytoplankton south of Australia is that of the subsurface chlorophyll maximum (SCM) that has consistently been observed (Yamaguchi and Shibata 1982, Kopczynska et al. 2001, Parslow et al. 2001). The depth of the SCM (to 150m) makes it particularly relevant to the CPR survey, possibly concentrating zooplankton below the CPR sampling depth (typically > 20m), and causing an underestimation of densities. Furthermore, the SCM varies in depth and strength, both zonally and seasonally and is consequently a potentially important source of both spatial and temporal variation. There is therefore an urgent need for seasonal studies of the fine-scale vertical distribution (upper 200m) of zooplankton communities in the Australian sector of the Southern Ocean focussing on the effects of the SCM.

Over the sampling period of this thesis both diel and seasonal cycles were important sources of variation in intra- and inter-zonal zooplankton community structure. Day samples typically had reduced zooplankton densities (e.g. Figure 3.5;

Figure 4.4b) and species richness (Table 4.2 and Table 4.4), although biogeographic zones were still identifiable from these data. In view of the differences between night and day samples there is a need to separate them in order to obtain a true picture of spatial variation and temporal variation at scales of greater than one day. Seasonal successions were a major source of temporal variation in both zooplankton densities and community structure in the study area (Chapters 5 and 6). Single transect (snapshot) studies may therefore result in spurious assumptions being made about the community structure of a zone. Furthermore, combining snapshot studies conducted over a number of years may potentially result in the misinterpretation of seasonal successions as inter-annual and long-term patterns. Seasonal data are therefore essential for both ecological studies and long-term monitoring as they put intra- and inter-zonal variation of zooplankton communities in the context of annual cycles.

The importance of diel and seasonal cycles to long-term monitoring extends beyond simply the variability that they introduce to observed zooplankton community structure. They are fundamental ecological processes that may be significantly altered by environmental change (Broekhuizen and McKenzie 1995, Hays et al. 1996, Planque and Fromentin 1996, Beare et al. 1998, Hirst and Batten 1998, Beare and McKenzie 1999b). Future research in the Southern Ocean CPR programme needs to identify inter-annual variation in the timing, duration and / or strength of diel and seasonal cycles, all of which are potentially important indicators of changing ecosystem dynamics in response to a changing environment.

A facet of seasonality highlighted by this study, and one that needs to be quantified urgently, is the relationship between the catchability of zooplankton and the size structure of their populations. The 270μm mesh used by the CPR survey under-samples *Oithona* spp. and the early copepodite stages (at least C1 to C3) of small calanoid copepod species (particularly *Ctenocalanus citer*, and to a lesser extent *Clausocalanus* spp.). Due to seasonal cycles of populations, this may result in spring / early summer under-estimation of densities. Related to this is the potential reduction of mesh size by the presence of large diatoms, resulting in an increased sampling efficiency of small copepods. The occurrence, densities and community structure of diatoms varies both temporally and seasonally. In this study high diatom densities were observed in the CPR samples through most of the season in the seasonal ice zone, while only being present in the northern Antarctic Zone and Inter Polar Frontal Zone in December. Consequently, if the presence of diatoms does

increase the catchability of small plankton, they may be an important source of variation (zonal and seasonal) in zooplankton densities. The influence of copepod size and diatoms on catchability should be investigated through sampling with finer mesh sizes (~ 100μm) over a full seasonal cycle.

The spatio-temporal data collected during this study provided baseline data on the zonation and seasonal cycles of zooplankton communities in the Southern Ocean south of Australia. The major role played by the physical environment, particularly fronts, in determining community structure reflected the sensitivity of the zooplankton to their surroundings, and highlighted their value as indicators of environmental change (e.g. ocean warming). The strongest physical front, the northern branch of the Sub-Antarctic Front (SAF-N), was also the strongest biogeographic boundary. The "warm water" sub-tropical and temperate taxa that occurred to the north of this front may be important indicators of a warming of the waters to the south. Similarly, the suite of taxa unique to the seasonal ice zone may be important indicators of fluctuations in sea-ice extent and / or changes in ecological processes associated with this habitat.

Changes in the contributions of common species to community structure, or range expansions, may also be seen as evidence for environmental change. Shifts in dominance may have serious implications for ecosystem functioning (e.g. vertical flux) due to inter-species interactions. The coupling of species' life-cycles may result in positive (increased food supply) or negative (competition) feedbacks for one species in response to the increased densities of another. Some evidence for this was presented in this study, including high densities of chaetognaths in association with high densities of copepods (food supply), and a negative correlation between salps and copepod / krill larvae densities (competition). Knowledge of such interactions may be essential to understanding the link between community and environmental changes.

Section 1.1 highlighted some of the accumulating evidence for a changing climate in the Southern Ocean. Recently Atkinson et al. (2004) combined krill and salp data accumulated by nine countries between 1926 – 1939 and 1976 – 2003 to demonstrate that krill biomass has decreased in the southwest Atlantic since the 1970's, correlating with ocean warming and a decline in sea-ice extent. Conversely, salps have expanded their range southwards. This community shift has had a significant effect on trophic dynamics, with krill shortages negatively impacting on the recruitment of vertebrate predators (Reid and Croxall 2001). There is an urgent

need for monitoring programmes, with consistent methodology and sampling continuity, in order to understand future ecological change. Long-term monitoring will potentially provide insights into the ecosystem impacts of both short term physical cycles, such as the Antarctic Circumpolar Wave (White and Peterson 1996), and decadal scale environmental shifts.

"The problem is that long-term monitoring is often incompatible with short-term decisions about funding. Once a continuous sequence of data is broken it can never be recovered."

- Nick Carter, Rothamsted Insect Survey (1989)

This study has demonstrated that the Southern Ocean CPR survey has the potential to be an accurate monitor of ecological change, focussing on the component of the ecosystem (plankton) that is most sensitive to environmental change and, at the same time, the basis of all Southern Ocean food webs. In addition, long-term data sets accumulated by this survey have the potential to contribute significantly to our understanding of zooplankton spatial and ecological dynamics. The success of 75 years of sampling by the northern hemisphere CPR survey is surely proof enough of the value of a sister survey in the Southern Ocean. It is my hope that the data presented in this thesis have contributed to the foundation of the Southern Ocean CPR Survey. It is with great anticipation that I look forward to the years to come, and what this survey will teach us about Southern Ocean and Antarctic marine ecosystems.

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Appendices

Appendix 1. List of Continuous Plankton Recorder and NORPAC net samples used in this thesis, collected between October 2001 and March 2002.

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
1	1	17/10/01	5:49	Aurora Australis	CPR	-53.99	132.74	5.04	~10.5
1	2	17/10/01	6:11	Aurora Australis	CPR	-53.93	132.83	4.84	~10.5
1	3	17/10/01	6:33	Aurora Australis	CPR	-53.86	132.92	5.01	~10.5
1	4	17/10/01	6:56	Aurora Australis	CPR	-53.80	133.01	5.15	~10.5
1	5	17/10/01	7:18	Aurora Australis	CPR	-53.73	133.10	4.99	~10.5
1	6	17/10/01	7:40	Aurora Australis	CPR	-53.67	133.18	4.94	~10.5
1	7	17/10/01	8:02	Aurora Australis	CPR	-53.60	133.26	4.88	~10.5
1	8	17/10/01	8:25	Aurora Australis	CPR	-53.54	133.35	5.03	~10.5
1	9	17/10/01	8:48	Aurora Australis	CPR	-53.47	133.45	5.11	~10.5
1	10	17/10/01	9:10	Aurora Australis	CPR	-53.41	133.54	4.92	~10.5
1	11	17/10/01	9:32	Aurora Australis	CPR	-53.35	133.63	5.02	~10.5
1	12	17/10/01	9:54	Aurora Australis	CPR	-53.29	133.72	4.94	~10.5
1	13	17/10/01	10:17	Aurora Australis	CPR	-53.22	133.82	5.09	~10.5
1	14	17/10/01	10:40	Aurora Australis	CPR	-53.16	133.91	5.01	~10.5
1	15	17/10/01	11:03	Aurora Australis	CPR	-53.10	134.00	4.98	~10.5
1	16	17/10/01	11:27	Aurora Australis	CPR	-53.03	134.09	5.09	~10.5
1	17	17/10/01	11:50	Aurora Australis	CPR	-52.98	134.18	4.86	~10.5
1	18	17/10/01	12:14	Aurora Australis	CPR	-52.91	134.28	5.16	~10.5
1	19	17/10/01	12:38	Aurora Australis	CPR	-52.85	134.38	4.97	~10.5
1	20	17/10/01	13:02	Aurora Australis	CPR	-52.79	134.47	4.91	~10.5
1	21	17/10/01	13:27	Aurora Australis	CPR	-52.73	134.57	5.07	~10.5
1	22	17/10/01	13:51	Aurora Australis	CPR	-52.67	134.66	4.93	~10.5
1	23	17/10/01	14:15	Aurora Australis	CPR	-52.62	134.76	5.01	~10.5
1	24	17/10/01	14:39	Aurora Australis	CPR	-52.56	134.86	5.06	~10.5
1	25	17/10/01	15:02	Aurora Australis	CPR	-52.50	134.95	4.97	~10.5
1	26	17/10/01	15:25	Aurora Australis	CPR	-52.44	135.04	4.99	~10.5
1	27	17/10/01	15:48	Aurora Australis	CPR	-52.37	135.14	4.99	~10.5
1	28	17/10/01	16:11	Aurora Australis	CPR	-52.31	135.23	5.00	~10.5
1	29	17/10/01	16:34	Aurora Australis	CPR	-52.25	135.32	5.02	~10.5
1	30	17/10/01	16:57	Aurora Australis	CPR	-52.19	135.42	5.08	~10.5
1	31	17/10/01	17:19	Aurora Australis	CPR	-52.13	135.51	4.86	~10.5
1	32	17/10/01	17:42	Aurora Australis	CPR	-52.07	135.60	5.07	~10.5
1	33	17/10/01	18:04	Aurora Australis	CPR	-52.01	135.69	4.88	~10.5
1	34	17/10/01	18:27	Aurora Australis	CPR	-51.95	135.78	5.04	~10.5
1	35	17/10/01	18:50	Aurora Australis	CPR	-51.88	135.87	5.00	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
1	36	17/10/01	19:13	Aurora Australis	CPR	-51.82	135.96	5.02	~10.5
1	37	17/10/01	19:36	Aurora Australis	CPR	-51.76	136.05	5.04	~10.5
1	38	17/10/01	19:59	Aurora Australis	CPR	-51.70	136.14	5.02	~10.5
1	39	17/10/01	20:21	Aurora Australis	CPR	-51.64	136.23	4.90	~10.5
1	40	17/10/01	20:44	Aurora Australis	CPR	-51.57	136.32	5.07	~10.5
1	41	17/10/01	21:07	Aurora Australis	CPR	-51.51	136.41	5.08	~10.5
1	42	17/10/01	21:29	Aurora Australis	CPR	-51.45	136.50	4.86	~10.5
1	43	17/10/01	21:52	Aurora Australis	CPR	-51.38	136.59	5.18	~10.5
1	44	17/10/01	22:14	Aurora Australis	CPR	-51.32	136.67	4.94	~10.5
1	45	17/10/01	22:44	Aurora Australis	CPR	-51.24	136.79	4.94	~10.5
1	46	17/10/01	23:06	Aurora Australis	CPR	-51.18	136.87	4.85	~10.5
1	47	17/10/01	23:29	Aurora Australis	CPR	-51.11	136.96	5.09	~10.5
1	48	17/10/01	23:52	Aurora Australis	CPR	-51.05	137.05	5.04	~10.5
1	49	18/10/01	0:14	Aurora Australis	CPR	-50.99	137.13	4.88	~10.5
1	50	18/10/01	0:37	Aurora Australis	CPR	-50.92	137.22	4.99	~10.5
1	51	18/10/01	1:00	Aurora Australis	CPR	-50.86	137.31	5.08	~10.5
1	52	18/10/01	1:22	Aurora Australis	CPR	-50.80	137.40	4.95	~10.5
1	53	18/10/01	1:44	Aurora Australis	CPR	-50.74	137.48	5.02	~10.5
1	54	18/10/01	2:06	Aurora Australis	CPR	-50.67	137.57	4.95	~10.5
1	55	18/10/01	2:29	Aurora Australis	CPR	-50.61	137.66	5.18	~10.5
1	56	18/10/01	2:51	Aurora Australis	CPR	-50.55	137.75	4.96	~10.5
1	57	18/10/01	3:13	Aurora Australis	CPR	-50.49	137.83	4.88	~10.5
1	58	18/10/01	3:36	Aurora Australis	CPR	-50.42	137.92	5.16	~10.5
1	59	18/10/01	3:58	Aurora Australis	CPR	-50.36	138.00	4.92	~10.5
1	60	18/10/01	4:20	Aurora Australis	CPR	-50.30	138.08	4.91	~10.5
1	61	18/10/01	4:43	Aurora Australis	CPR	-50.23	138.17	5.13	~10.5
1	62	18/10/01	5:05	Aurora Australis	CPR	-50.17	138.26	4.99	~10.5
1	63	18/10/01	5:27	Aurora Australis	CPR	-50.11	138.34	4.90	~10.5
1	64	18/10/01	5:50	Aurora Australis	CPR	-50.04	138.43	5.15	~10.5
1	65	18/10/01	6:12	Aurora Australis	CPR	-49.98	138.51	4.90	~10.5
1	66	18/10/01	6:35	Aurora Australis	CPR	-49.92	138.60	5.11	~10.5
1	67	18/10/01	6:57	Aurora Australis	CPR	-49.86	138.69	4.97	~10.5
1	68	18/10/01	7:19	Aurora Australis	CPR	-49.80	138.77	4.90	~10.5
1	69	18/10/01	7:42	Aurora Australis	CPR	-49.74	138.86	5.05	~10.5
1	70	18/10/01	8:05	Aurora Australis	CPR	-49.67	138.95	5.09	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
1	71	18/10/01	8:27	Aurora Australis	CPR	-49.62	139.04	4.85	~10.5
1	72	18/10/01	8:50	Aurora Australis	CPR	-49.56	139.13	4.97	~10.5
1	73	18/10/01	9:14	Aurora Australis	CPR	-49.50	139.23	5.18	~10.5
1	74	18/10/01	9:37	Aurora Australis	CPR	-49.44	139.32	4.91	~10.5
1	75	18/10/01	10:00	Aurora Australis	CPR	-49.38	139.41	5.03	~10.5
1	76	18/10/01	10:23	Aurora Australis	CPR	-49.32	139.50	5.03	~10.5
1	77	18/10/01	10:46	Aurora Australis	CPR	-49.26	139.59	4.96	~10.5
1	78	18/10/01	11:09	Aurora Australis	CPR	-49.20	139.68	5.02	~10.5
1	79	18/10/01	11:32	Aurora Australis	CPR	-49.14	139.77	5.00	~10.5
1	80	18/10/01	11:54	Aurora Australis	CPR	-49.09	139.85	4.85	~10.5
1	81	18/10/01	12:17	Aurora Australis	CPR	-49.02	139.94	5.06	~10.5
1	82	18/10/01	12:40	Aurora Australis	CPR	-48.96	140.02	5.04	~10.5
1	83	18/10/01	13:03	Aurora Australis	CPR	-48.90	140.11	5.10	~10.5
1	84	18/10/01	13:25	Aurora Australis	CPR	-48.84	140.20	4.95	~10.5
1	85	18/10/01	13:48	Aurora Australis	CPR	-48.78	140.28	5.02	~10.5
1	86	18/10/01	14:11	Aurora Australis	CPR	-48.72	140.37	4.95	~10.5
1	87	18/10/01	14:34	Aurora Australis	CPR	-48.65	140.45	4.99	~10.5
1	88	18/10/01	14:57	Aurora Australis	CPR	-48.59	140.53	4.93	~10.5
1	89	18/10/01	15:21	Aurora Australis	CPR	-48.53	140.62	5.17	~10.5
1	90	18/10/01	15:44	Aurora Australis	CPR	-48.46	140.70	5.01	~10.5
1	91	18/10/01	16:07	Aurora Australis	CPR	-48.40	140.78	4.96	~10.5
1	92	18/10/01	16:30	Aurora Australis	CPR	-48.34	140.86	5.02	~10.5
1	93	18/10/01	16:52	Aurora Australis	CPR	-48.28	140.94	4.91	~10.5
1	94	18/10/01	17:15	Aurora Australis	CPR	-48.21	141.03	5.03	~10.5
1	95	18/10/01	17:37	Aurora Australis	CPR	-48.15	141.11	4.87	~10.5
1	96	18/10/01	17:59	Aurora Australis	CPR	-48.09	141.19	5.01	~10.5
1	97	18/10/01	18:22	Aurora Australis	CPR	-48.02	141.27	5.15	~10.5
1	98	18/10/01	18:44	Aurora Australis	CPR	-47.96	141.36	4.97	~10.5
1	99	18/10/01	19:05	Aurora Australis	CPR	-47.90	141.44	4.91	~10.5
1	100	18/10/01	19:26	Aurora Australis	CPR	-47.84	141.53	4.95	~10.5
1	101	18/10/01	19:48	Aurora Australis	CPR	-47.78	141.61	5.19	~10.5
1	102	18/10/01	20:09	Aurora Australis	CPR	-47.72	141.70	4.90	~10.5
1	103	18/10/01	20:30	Aurora Australis	CPR	-47.66	141.78	4.89	~10.5
1	104	18/10/01	20:52	Aurora Australis	CPR	-47.60	141.86	5.05	~10.5
1	105	18/10/01	21:14	Aurora Australis	CPR	-47.54	141.95	5.06	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
1	106	18/10/01	21:36	Aurora Australis	CPR	-47.47	142.03	5.04	~10.5
1	107	18/10/01	21:58	Aurora Australis	CPR	-47.41	142.11	5.01	~10.5
1	108	18/10/01	22:20	Aurora Australis	CPR	-47.35	142.20	5.02	~10.5
1	109	18/10/01	22:42	Aurora Australis	CPR	-47.29	142.28	4.93	~10.5
1	110	18/10/01	23:05	Aurora Australis	CPR	-47.23	142.36	5.03	~10.5
1	111	18/10/01	23:27	Aurora Australis	CPR	-47.17	142.44	4.86	~10.5
1	112	18/10/01	23:50	Aurora Australis	CPR	-47.11	142.53	5.09	~10.5
1	113	19/10/01	0:13	Aurora Australis	CPR	-47.05	142.62	5.08	~10.5
2	114	2/11/2001	-	Aurora Australis	NORPAC	47.13	144.90	-	0-20
2	115	6/11/2001	19:20	Aurora Australis	NORPAC	48.00	144.67	-	0-20
2	116	6/11/2001	11:30	Aurora Australis	NORPAC	48.78	144.32	-	0-20
2	117	7/11/2001	18:00	Aurora Australis	NORPAC	49.27	144.10	-	0-20
2	118	8/11/2001	6:30	Aurora Australis	NORPAC	49.89	143.80	-	0-20
2	119	9/11/2001	2:00	Aurora Australis	NORPAC	51.00	143.27	-	0-20
2	120	11/11/2001	10:00	Aurora Australis	NORPAC	52.37	142.53	-	0-20
2	121	11/11/2001	15:30	Aurora Australis	NORPAC	52.67	142.39	-	0-20
2	122	11/11/2001	22:15	Aurora Australis	NORPAC	53.13	142.14	-	0-20
2	123	12/11/2001	4:00	Aurora Australis	NORPAC	53.43	141.95	-	0-20
2	124	13/11/01	10:50	Aurora Australis	NORPAC	53.73	141.85	-	0-20
2	125	14/11/01	22:12	Aurora Australis	NORPAC	54.53	141.33	-	0-20
2	126	15/11/01	4:00	Aurora Australis	NORPAC	55.02	141.02	-	0-20
2	127	15/11/01	20:30	Aurora Australis	NORPAC	55.93	140.41	-	0-20
2	128	16/11/01	11:30	Aurora Australis	NORPAC	56.93	139.85	-	0-20
2	129	17/11/01	21:30	Aurora Australis	NORPAC	57.85	139.85	-	0-20
2	130	18/11/01	18:00	Aurora Australis	NORPAC	58.85	139.85	-	0-20
2	131	19/11/01	0:15	Aurora Australis	NORPAC	59.35	139.85	-	0-20
2	132	19/11/01	8:30	Aurora Australis	NORPAC	59.85	139.85	-	0-20
2	133	21/11/01	3:45	Aurora Australis	NORPAC	60.85	139.85	-	0-20
2	134	22/11/01	9:45	Aurora Australis	NORPAC	61.35	139.85	-	0-20
2	135	22/11/01	14:00	Aurora Australis	NORPAC	61.85	139.85	-	0-20
2	136	22/11/01	22:30	Aurora Australis	NORPAC	62.35	139.85	-	0-20
2	137	24/11/01	6:30	Aurora Australis	NORPAC	62.85	139.85	-	0-20
2	138	24/11/01	12:30	Aurora Australis	NORPAC	63.37	139.85	-	0-20
2	139	25/11/01	5:30	Aurora Australis	NORPAC	63.92	139.85	-	0-20
2	140	25/11/01	8:30	Aurora Australis	NORPAC	64.17	140.42	-	0-20

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
2	141	26/11/01	15:23	Aurora Australis	NORPAC	64.51	141.34	-	0-20
2	142	27/11/01	5:30	Aurora Australis	NORPAC	65.05	142.53	-	0-20
2	143	27/11/01	18:27	Aurora Australis	NORPAC	65.53	143.17	-	0-20
2	144	28/11/01	2:55	Aurora Australis	NORPAC	65.77	142.93	-	0-20
2	145	28/11/01	11:10	Aurora Australis	NORPAC	66.00	143.15	-	0-20
2	146	2/11/2001	-	Aurora Australis	NORPAC	47.13	144.90	-	20-50
2	147	6/11/2001	19:20	Aurora Australis	NORPAC	48.00	144.67	-	20-50
2	148	6/11/2001	11:30	Aurora Australis	NORPAC	48.78	144.32	-	20-50
2	149	7/11/2001	18:00	Aurora Australis	NORPAC	49.27	144.10	-	20-50
2	150	8/11/2001	6:30	Aurora Australis	NORPAC	49.89	143.80	-	20-50
2	151	9/11/2001	2:00	Aurora Australis	NORPAC	51.00	143.27	-	20-50
2	152	11/11/2001	10:00	Aurora Australis	NORPAC	52.37	142.53	-	20-50
2	153	11/11/2001	15:30	Aurora Australis	NORPAC	52.67	142.39	-	20-50
2	154	11/11/2001	22:15	Aurora Australis	NORPAC	53.13	142.14	-	20-50
2	155	12/11/2001	4:00	Aurora Australis	NORPAC	53.43	141.95	-	20-50
2	156	13/11/01	10:50	Aurora Australis	NORPAC	53.73	141.85	-	20-50
2	157	14/11/01	22:12	Aurora Australis	NORPAC	54.53	141.33	-	20-50
2	158	15/11/01	4:00	Aurora Australis	NORPAC	55.02	141.02	-	20-50
2	159	15/11/01	20:30	Aurora Australis	NORPAC	55.93	140.41	-	20-50
2	160	16/11/01	11:30	Aurora Australis	NORPAC	56.93	139.85	-	20-50
2	161	17/11/01	21:30	Aurora Australis	NORPAC	57.85	139.85	-	20-50
2	162	18/11/01	18:00	Aurora Australis	NORPAC	58.85	139.85	-	20-50
2	163	19/11/01	0:15	Aurora Australis	NORPAC	59.35	139.85	-	20-50
2	164	19/11/01	8:30	Aurora Australis	NORPAC	59.85	139.85	-	20-50
2	165	21/11/01	3:45	Aurora Australis	NORPAC	60.85	139.85	-	20-50
2	166	22/11/01	9:45	Aurora Australis	NORPAC	61.35	139.85	-	20-50
2	167	22/11/01	14:00	Aurora Australis	NORPAC	61.85	139.85	-	20-50
2	168	22/11/01	22:30	Aurora Australis	NORPAC	62.35	139.85	-	20-50
2	169	24/11/01	6:30	Aurora Australis	NORPAC	62.85	139.85	-	20-50
2	170	24/11/01	12:30	Aurora Australis	NORPAC	63.37	139.85	-	20-50
2	171	25/11/01	5:30	Aurora Australis	NORPAC	63.92	139.85	-	20-50
2	172	25/11/01	8:30	Aurora Australis	NORPAC	64.17	140.42	-	20-50
2	173	26/11/01	15:23	Aurora Australis	NORPAC	64.51	141.34	-	20-50
2	174	27/11/01	5:30	Aurora Australis	NORPAC	65.05	142.53	-	20-50
2	175	27/11/01	18:27	Aurora Australis	NORPAC	65.53	143.17	-	20-50

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
2	176	28/11/01	2:55	Aurora Australis	NORPAC	65.77	142.93	-	20-50
2	177	28/11/01	11:10	Aurora Australis	NORPAC	66.00	143.15	-	20-50
2	178	2/11/2001	-	Aurora Australis	NORPAC	47.13	144.90	-	50-100
2	179	6/11/2001	19:20	Aurora Australis	NORPAC	48.00	144.67	-	50-100
2	180	6/11/2001	11:30	Aurora Australis	NORPAC	48.78	144.32	-	50-100
2	181	7/11/2001	18:00	Aurora Australis	NORPAC	49.27	144.10	-	50-100
2	182	8/11/2001	6:30	Aurora Australis	NORPAC	49.89	143.80	-	50-100
2	183	9/11/2001	2:00	Aurora Australis	NORPAC	51.00	143.27	-	50-100
2	184	11/11/2001	10:00	Aurora Australis	NORPAC	52.37	142.53	-	50-100
2	185	11/11/2001	15:30	Aurora Australis	NORPAC	52.67	142.39	-	50-100
2	186	11/11/2001	22:15	Aurora Australis	NORPAC	53.13	142.14	-	50-100
2	187	12/11/2001	4:00	Aurora Australis	NORPAC	53.43	141.95	-	50-100
2	188	13/11/01	10:50	Aurora Australis	NORPAC	53.73	141.85	-	50-100
2	189	14/11/01	22:12	Aurora Australis	NORPAC	54.53	141.33	-	50-100
2	190	15/11/01	4:00	Aurora Australis	NORPAC	55.02	141.02	-	50-100
2	191	15/11/01	20:30	Aurora Australis	NORPAC	55.93	140.41	-	50-100
2	192	16/11/01	11:30	Aurora Australis	NORPAC	56.93	139.85	-	50-100
2	193	17/11/01	21:30	Aurora Australis	NORPAC	57.85	139.85	-	50-100
2	194	18/11/01	18:00	Aurora Australis	NORPAC	58.85	139.85	-	50-100
2	195	19/11/01	0:15	Aurora Australis	NORPAC	59.35	139.85	-	50-100
2	196	19/11/01	8:30	Aurora Australis	NORPAC	59.85	139.85	-	50-100
2	197	21/11/01	3:45	Aurora Australis	NORPAC	60.85	139.85	-	50-100
2	198	22/11/01	9:45	Aurora Australis	NORPAC	61.35	139.85	-	50-100
2	199	22/11/01	14:00	Aurora Australis	NORPAC	61.85	139.85	-	50-100
2	200	22/11/01	22:30	Aurora Australis	NORPAC	62.35	139.85	-	50-100
2	201	24/11/01	6:30	Aurora Australis	NORPAC	62.85	139.85	-	50-100
2	202	24/11/01	12:30	Aurora Australis	NORPAC	63.37	139.85	-	50-100
2	203	25/11/01	5:30	Aurora Australis	NORPAC	63.92	139.85	-	50-100
2	204	25/11/01	8:30	Aurora Australis	NORPAC	64.17	140.42	-	50-100
2	205	26/11/01	15:23	Aurora Australis	NORPAC	64.51	141.34	-	50-100
2	206	27/11/01	5:30	Aurora Australis	NORPAC	65.05	142.53	-	50-100
2	207	27/11/01	18:27	Aurora Australis	NORPAC	65.53	143.17	-	50-100
2	208	28/11/01	2:55	Aurora Australis	NORPAC	65.77	142.93	-	50-100
2	209	28/11/01	11:10	Aurora Australis	NORPAC	66.00	143.15	-	50-100
2	210	2/11/2001	-	Aurora Australis	NORPAC	47.13	144.90	-	100-150

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
2	**211**	6/11/2001	19:20	Aurora Australis	NORPAC	48.00	144.67	-	100-150
2	**212**	6/11/2001	11:30	Aurora Australis	NORPAC	48.78	144.32	-	100-150
2	**213**	7/11/2001	18:00	Aurora Australis	NORPAC	49.27	144.10	-	100-150
2	**214**	8/11/2001	6:30	Aurora Australis	NORPAC	49.89	143.80	-	100-150
2	**215**	9/11/2001	2:00	Aurora Australis	NORPAC	51.00	143.27	-	100-150
2	**216**	11/11/2001	10:00	Aurora Australis	NORPAC	52.37	142.53	-	100-150
2	**217**	11/11/2001	15:30	Aurora Australis	NORPAC	52.67	142.39	-	100-150
2	**218**	11/11/2001	22:15	Aurora Australis	NORPAC	53.13	142.14	-	100-150
2	**219**	12/11/2001	4:00	Aurora Australis	NORPAC	53.43	141.95	-	100-150
2	**220**	13/11/01	10:50	Aurora Australis	NORPAC	53.73	141.85	-	100-150
2	**221**	14/11/01	22:12	Aurora Australis	NORPAC	54.53	141.33	-	100-150
2	**222**	15/11/01	4:00	Aurora Australis	NORPAC	55.02	141.02	-	100-150
2	**223**	15/11/01	20:30	Aurora Australis	NORPAC	55.93	140.41	-	100-150
2	**224**	16/11/01	11:30	Aurora Australis	NORPAC	56.93	139.85	-	100-150
2	**225**	17/11/01	21:30	Aurora Australis	NORPAC	57.85	139.85	-	100-150
2	**226**	18/11/01	18:00	Aurora Australis	NORPAC	58.85	139.85	-	100-150
2	**227**	19/11/01	0:15	Aurora Australis	NORPAC	59.35	139.85	-	100-150
2	**228**	19/11/01	8:30	Aurora Australis	NORPAC	59.85	139.85	-	100-150
2	**229**	21/11/01	3:45	Aurora Australis	NORPAC	60.85	139.85	-	100-150
2	**230**	22/11/01	9:45	Aurora Australis	NORPAC	61.35	139.85	-	100-150
2	**231**	22/11/01	14:00	Aurora Australis	NORPAC	61.85	139.85	-	100-150
2	**232**	22/11/01	22:30	Aurora Australis	NORPAC	62.35	139.85	-	100-150
2	**233**	24/11/01	6:30	Aurora Australis	NORPAC	62.85	139.85	-	100-150
2	**234**	24/11/01	12:30	Aurora Australis	NORPAC	63.37	139.85	-	100-150
2	**235**	25/11/01	5:30	Aurora Australis	NORPAC	63.92	139.85	-	100-150
2	**236**	25/11/01	8:30	Aurora Australis	NORPAC	64.17	140.42	-	100-150
2	**237**	26/11/01	15:23	Aurora Australis	NORPAC	64.51	141.34	-	100-150
2	**238**	27/11/01	5:30	Aurora Australis	NORPAC	65.05	142.53	-	100-150
2	**239**	27/11/01	18:27	Aurora Australis	NORPAC	65.53	143.17	-	100-150
2	**240**	28/11/01	2:55	Aurora Australis	NORPAC	65.77	142.93	-	100-150
2	**241**	28/11/01	11:10	Aurora Australis	NORPAC	66.00	143.15	-	100-150
3	**242**	7/12/2001	08:17	Aurora Australis	CPR	-61.53	140.25	4.94	~10.5
3	**243**	7/12/2001	08:44	Aurora Australis	CPR	-61.46	140.21	4.92	~10.5
3	**244**	7/12/2001	09:12	Aurora Australis	CPR	-61.37	140.17	5.14	~10.5
3	**245**	7/12/2001	09:39	Aurora Australis	CPR	-61.29	140.13	4.98	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
3	246	7/12/2001	10:06	Aurora Australis	CPR	-61.22	140.08	4.86	~10.5
3	247	7/12/2001	10:36	Aurora Australis	CPR	-61.14	140.00	5.07	~10.5
3	248	7/12/2001	11:08	Aurora Australis	CPR	-61.06	139.93	5.06	~10.5
3	249	7/12/2001	11:41	Aurora Australis	CPR	-60.99	139.84	4.94	~10.5
3	250	7/12/2001	12:13	Aurora Australis	CPR	-60.91	139.79	4.93	~10.5
3	251	7/12/2001	12:47	Aurora Australis	CPR	-60.85	139.78	4.75	~10.5
3	252	8/12/2001	00:30	Aurora Australis	CPR	-60.73	139.93	4.80	~10.5
3	253	8/12/2001	00:52	Aurora Australis	CPR	-60.64	139.93	5.08	~10.5
3	254	8/12/2001	01:14	Aurora Australis	CPR	-60.56	139.93	5.12	~10.5
3	255	8/12/2001	01:35	Aurora Australis	CPR	-60.47	139.93	4.91	~10.5
3	256	8/12/2001	02:18	Aurora Australis	CPR	-60.43	139.80	5.08	~10.5
3	257	8/12/2001	02:41	Aurora Australis	CPR	-60.35	139.80	5.05	~10.5
3	258	8/12/2001	03:07	Aurora Australis	CPR	-60.27	139.82	5.01	~10.5
3	259	8/12/2001	03:26	Aurora Australis	CPR	-60.18	139.83	5.08	~10.5
3	260	8/12/2001	03:43	Aurora Australis	CPR	-60.10	139.83	4.77	~10.5
3	261	8/12/2001	04:01	Aurora Australis	CPR	-60.02	139.84	5.13	~10.5
3	262	8/12/2001	04:19	Aurora Australis	CPR	-59.93	139.84	5.12	~10.5
3	263	8/12/2001	04:36	Aurora Australis	CPR	-59.85	139.84	4.87	~10.5
3	264	8/12/2001	04:54	Aurora Australis	CPR	-59.77	139.84	5.05	~10.5
3	265	8/12/2001	05:12	Aurora Australis	CPR	-59.68	139.84	5.07	~10.5
3	266	8/12/2001	05:30	Aurora Australis	CPR	-59.60	139.84	5.03	~10.5
3	267	8/12/2001	05:48	Aurora Australis	CPR	-59.51	139.84	5.01	~10.5
3	268	8/12/2001	06:06	Aurora Australis	CPR	-59.43	139.85	5.01	~10.5
3	269	8/12/2001	06:24	Aurora Australis	CPR	-59.35	139.85	4.98	~10.5
3	270	8/12/2001	06:42	Aurora Australis	CPR	-59.27	139.86	4.94	~10.5
3	271	8/12/2001	07:01	Aurora Australis	CPR	-59.18	139.87	5.21	~10.5
3	272	8/12/2001	07:19	Aurora Australis	CPR	-59.10	139.87	4.91	~10.5
3	273	8/12/2001	07:38	Aurora Australis	CPR	-59.01	139.88	5.17	~10.5
3	274	8/12/2001	07:56	Aurora Australis	CPR	-58.93	139.89	4.86	~10.5
3	275	8/12/2001	08:15	Aurora Australis	CPR	-58.84	139.89	5.12	~10.5
3	276	8/12/2001	08:33	Aurora Australis	CPR	-58.76	139.90	4.85	~10.5
3	277	8/12/2001	08:52	Aurora Australis	CPR	-58.68	139.91	5.07	~10.5
3	278	8/12/2001	09:11	Aurora Australis	CPR	-58.60	139.91	5.02	~10.5
3	279	8/12/2001	09:30	Aurora Australis	CPR	-58.51	139.92	4.96	~10.5
3	280	8/12/2001	09:50	Aurora Australis	CPR	-58.43	139.93	5.19	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
3	**281**	8/12/2001	10:09	Aurora Australis	CPR	-58.34	139.94	4.91	~10.5
3	**282**	8/12/2001	10:29	Aurora Australis	CPR	-58.26	139.95	5.15	~10.5
3	**283**	8/12/2001	10:48	Aurora Australis	CPR	-58.18	139.95	4.94	~10.5
3	**284**	8/12/2001	11:07	Aurora Australis	CPR	-58.09	139.96	4.95	~10.5
3	**285**	8/12/2001	11:26	Aurora Australis	CPR	-58.01	139.97	4.95	~10.5
3	**286**	8/12/2001	11:46	Aurora Australis	CPR	-57.93	139.97	5.21	~10.5
3	**287**	8/12/2001	12:11	Aurora Australis	CPR	-57.84	139.97	5.02	~10.5
3	**288**	8/12/2001	12:34	Aurora Australis	CPR	-57.76	139.96	4.89	~10.5
3	**289**	8/12/2001	13:00	Aurora Australis	CPR	-57.67	139.96	5.18	~10.5
3	**290**	8/12/2001	13:35	Aurora Australis	CPR	-57.59	139.96	4.98	~10.5
3	**291**	8/12/2001	14:07	Aurora Australis	CPR	-57.51	139.95	5.06	~10.5
3	**292**	8/12/2001	14:41	Aurora Australis	CPR	-57.42	139.94	5.02	~10.5
3	**293**	8/12/2001	15:16	Aurora Australis	CPR	-57.34	139.93	4.97	~10.5
3	**294**	8/12/2001	15:51	Aurora Australis	CPR	-57.26	139.92	5.01	~10.5
3	**295**	8/12/2001	16:26	Aurora Australis	CPR	-57.17	139.90	5.08	~10.5
3	**296**	8/12/2001	17:00	Aurora Australis	CPR	-57.09	139.88	4.99	~10.5
3	**297**	8/12/2001	17:36	Aurora Australis	CPR	-57.01	139.86	4.96	~10.5
3	**298**	8/12/2001	18:24	Aurora Australis	CPR	-56.93	139.85	5.08	~10.5
3	**299**	9/12/2001	17:05	Aurora Australis	CPR	-56.74	139.96	4.87	~10.5
3	**300**	9/12/2001	17:23	Aurora Australis	CPR	-56.67	140.02	5.02	~10.5
3	**301**	9/12/2001	17:41	Aurora Australis	CPR	-56.59	140.07	5.03	~10.5
3	**302**	9/12/2001	17:59	Aurora Australis	CPR	-56.51	140.13	5.00	~10.5
3	**303**	9/12/2001	18:17	Aurora Australis	CPR	-56.43	140.18	5.03	~10.5
3	**304**	9/12/2001	18:35	Aurora Australis	CPR	-56.35	140.23	4.97	~10.5
3	**305**	9/12/2001	18:53	Aurora Australis	CPR	-56.28	140.29	4.96	~10.5
3	**306**	9/12/2001	19:11	Aurora Australis	CPR	-56.20	140.34	4.99	~10.5
3	**307**	9/12/2001	19:29	Aurora Australis	CPR	-56.12	140.39	4.95	~10.5
3	**308**	9/12/2001	19:47	Aurora Australis	CPR	-56.04	140.44	5.05	~10.5
3	**309**	9/12/2001	20:05	Aurora Australis	CPR	-55.96	140.50	5.10	~10.5
3	**310**	9/12/2001	20:22	Aurora Australis	CPR	-55.89	140.54	4.84	~10.5
3	**311**	9/12/2001	20:40	Aurora Australis	CPR	-55.81	140.59	5.10	~10.5
3	**312**	9/12/2001	20:56	Aurora Australis	CPR	-55.74	140.64	4.30	~10.5
3	**313**	10/12/2001	07:20	Aurora Australis	CPR	-53.55	142.03	4.90	~10.5
3	**314**	10/12/2001	07:42	Aurora Australis	CPR	-53.47	142.08	5.12	~10.5
3	**315**	10/12/2001	08:06	Aurora Australis	CPR	-53.40	142.14	4.96	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
3	316	10/12/2001	08:25	Aurora Australis	CPR	-53.32	142.19	4.93	~10.5
3	317	10/12/2001	08:44	Aurora Australis	CPR	-53.24	142.24	5.14	~10.5
3	318	10/12/2001	09:03	Aurora Australis	CPR	-53.16	142.28	5.07	~10.5
3	319	10/12/2001	09:22	Aurora Australis	CPR	-53.08	142.33	5.05	~10.5
3	320	10/12/2001	09:41	Aurora Australis	CPR	-53.00	142.38	5.10	~10.5
3	321	10/12/2001	09:59	Aurora Australis	CPR	-52.92	142.42	4.85	~10.5
3	322	10/12/2001	10:18	Aurora Australis	CPR	-52.84	142.46	5.19	~10.5
3	323	10/12/2001	10:36	Aurora Australis	CPR	-52.76	142.50	4.96	~10.5
3	324	10/12/2001	10:54	Aurora Australis	CPR	-52.68	142.55	5.01	~10.5
3	325	10/12/2001	11:12	Aurora Australis	CPR	-52.60	142.59	5.01	~10.5
3	326	10/12/2001	11:31	Aurora Australis	CPR	-52.52	142.64	5.23	~10.5
3	327	10/12/2001	11:49	Aurora Australis	CPR	-52.44	142.68	5.04	~10.5
3	328	10/12/2001	12:06	Aurora Australis	CPR	-52.37	142.72	4.81	~10.5
3	329	10/12/2001	12:24	Aurora Australis	CPR	-52.28	142.75	5.04	~10.5
3	330	10/12/2001	12:43	Aurora Australis	CPR	-52.20	142.79	5.30	~10.5
3	331	10/12/2001	13:01	Aurora Australis	CPR	-52.12	142.83	5.03	~10.5
3	332	10/12/2001	13:19	Aurora Australis	CPR	-52.04	142.87	5.00	~10.5
3	333	10/12/2001	13:37	Aurora Australis	CPR	-51.96	142.91	5.02	~10.5
3	334	10/12/2001	13:55	Aurora Australis	CPR	-51.88	142.94	5.04	~10.5
3	335	10/12/2001	14:13	Aurora Australis	CPR	-51.80	142.97	5.06	~10.5
3	336	10/12/2001	14:31	Aurora Australis	CPR	-51.71	143.01	5.03	~10.5
3	337	10/12/2001	14:49	Aurora Australis	CPR	-51.63	143.04	5.04	~10.5
3	338	10/12/2001	15:07	Aurora Australis	CPR	-51.55	143.08	5.01	~10.5
3	339	10/12/2001	15:25	Aurora Australis	CPR	-51.47	143.12	5.00	~10.5
3	340	10/12/2001	15:43	Aurora Australis	CPR	-51.39	143.15	4.99	~10.5
3	341	10/12/2001	16:01	Aurora Australis	CPR	-51.31	143.19	5.01	~10.5
3	342	10/12/2001	16:19	Aurora Australis	CPR	-51.23	143.22	5.08	~10.5
3	343	10/12/2001	16:37	Aurora Australis	CPR	-51.15	143.25	5.14	~10.5
3	344	10/12/2001	16:54	Aurora Australis	CPR	-51.07	143.28	4.88	~10.5
3	345	10/12/2001	19:56	Aurora Australis	CPR	-51.00	143.32	5.27	~10.5
3	346	10/12/2001	20:24	Aurora Australis	CPR	-50.93	143.37	4.91	~10.5
3	347	10/12/2001	20:56	Aurora Australis	CPR	-50.86	143.42	5.16	~10.5
3	348	10/12/2001	22:41	Aurora Australis	CPR	-50.93	143.34	5.03	~10.5
3	349	10/12/2001	23:44	Aurora Australis	CPR	-51.00	143.26	5.02	~10.5
3	350	11/12/2001	00:49	Aurora Australis	CPR	-51.07	143.19	5.04	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
3	351	11/12/2001	01:56	Aurora Australis	CPR	-51.14	143.11	5.08	~10.5
3	352	11/12/2001	03:02	Aurora Australis	CPR	-51.21	143.05	5.02	~10.5
3	353	11/12/2001	04:11	Aurora Australis	CPR	-51.29	143.01	5.06	~10.5
4	354	10/1/2002	6:10	Hakuho Maru	CPR	65.49	140.05	4.97	~10.5
4	355	10/1/2002	6:30	Hakuho Maru	CPR	65.41	140.03	4.95	~10.5
4	356	10/1/2002	6:50	Hakuho Maru	CPR	65.33	140.02	4.93	~10.5
4	357	10/1/2002	7:11	Hakuho Maru	CPR	65.24	140.00	5.12	~10.5
4	358	10/1/2002	7:32	Hakuho Maru	CPR	65.16	139.99	5.02	~10.5
4	359	10/1/2002	7:52	Hakuho Maru	CPR	65.08	140.03	4.84	~10.5
4	360	10/1/2002	8:13	Hakuho Maru	CPR	65.00	140.11	5.09	~10.5
4	361	10/1/2002	8:34	Hakuho Maru	CPR	64.92	140.16	5.05	~10.5
4	362	10/1/2002	8:55	Hakuho Maru	CPR	64.84	140.16	4.97	~10.5
4	363	10/1/2002	9:16	Hakuho Maru	CPR	64.76	140.14	4.91	~10.5
4	364	10/1/2002	9:38	Hakuho Maru	CPR	64.68	140.12	5.08	~10.5
4	365	10/1/2002	10:02	Hakuho Maru	CPR	64.59	140.10	4.90	~10.5
4	366	10/1/2002	10:29	Hakuho Maru	CPR	64.51	140.07	5.04	~10.5
4	367	10/1/2002	10:57	Hakuho Maru	CPR	64.43	140.03	5.06	~10.5
4	368	10/1/2002	11:27	Hakuho Maru	CPR	64.35	139.98	4.97	~10.5
4	369	10/1/2002	12:00	Hakuho Maru	CPR	64.27	139.98	5.08	~10.5
4	370	10/1/2002	12:26	Hakuho Maru	CPR	64.22	140.11	4.89	~10.5
4	371	10/1/2002	12:55	Hakuho Maru	CPR	64.14	140.07	5.03	~10.5
4	372	10/1/2002	13:29	Hakuho Maru	CPR	64.06	140.00	5.07	~10.5
4	373	10/1/2002	13:59	Hakuho Maru	CPR	64.01	139.98	2.91	~10.5
4	374	13/1/2002	0:19	Hakuho Maru	CPR	63.92	139.98	4.75	~10.5
4	375	13/1/2002	0:39	Hakuho Maru	CPR	63.83	140.00	5.18	~10.5
4	376	13/1/2002	0:58	Hakuho Maru	CPR	63.75	140.00	4.90	~10.5
4	377	13/1/2002	1:17	Hakuho Maru	CPR	63.67	140.00	4.92	~10.5
4	378	13/1/2002	1:37	Hakuho Maru	CPR	63.58	140.00	5.21	~10.5
4	379	13/1/2002	1:56	Hakuho Maru	CPR	63.50	140.01	4.97	~10.5
4	380	13/1/2002	2:15	Hakuho Maru	CPR	63.42	140.01	4.90	~10.5
4	381	13/1/2002	2:35	Hakuho Maru	CPR	63.33	140.00	5.12	~10.5
4	382	13/1/2002	2:55	Hakuho Maru	CPR	63.25	140.00	5.04	~10.5
4	383	13/1/2002	3:15	Hakuho Maru	CPR	63.17	140.00	4.98	~10.5
4	384	13/1/2002	3:35	Hakuho Maru	CPR	63.08	140.00	5.04	~10.5
4	385	13/1/2002	3:59	Hakuho Maru	CPR	63.00	140.00	4.69	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
4	**386**	13/1/2002	12:32	Hakuho Maru	CPR	62.92	140.01	4.74	~10.5
4	**387**	13/1/2002	12:52	Hakuho Maru	CPR	62.84	140.00	5.20	~10.5
4	**388**	13/1/2002	13:11	Hakuho Maru	CPR	62.76	140.00	4.90	~10.5
4	**389**	13/1/2002	13:31	Hakuho Maru	CPR	62.67	140.00	5.14	~10.5
4	**390**	13/1/2002	13:50	Hakuho Maru	CPR	62.59	140.00	4.90	~10.5
4	**391**	13/1/2002	14:10	Hakuho Maru	CPR	62.50	140.00	5.12	~10.5
4	**392**	13/1/2002	14:29	Hakuho Maru	CPR	62.42	139.99	4.79	~10.5
4	**393**	13/1/2002	14:49	Hakuho Maru	CPR	62.34	139.99	4.98	~10.5
4	**394**	13/1/2002	15:09	Hakuho Maru	CPR	62.26	140.00	5.00	~10.5
4	**395**	13/1/2002	15:29	Hakuho Maru	CPR	62.17	140.00	5.03	~10.5
4	**396**	13/1/2002	15:49	Hakuho Maru	CPR	62.09	140.00	5.05	~10.5
4	**397**	13/1/2002	16:13	Hakuho Maru	CPR	62.00	140.00	5.14	~10.5
4	**398**	13/1/2002	16:16	Hakuho Maru	CPR	62.00	140.00	0.09	~10.5
4	**399**	14/1/2002	1:08	Hakuho Maru	CPR	61.93	140.01	4.87	~10.5
4	**400**	14/1/2002	1:28	Hakuho Maru	CPR	61.84	140.00	5.11	~10.5
4	**401**	14/1/2002	1:47	Hakuho Maru	CPR	61.76	140.00	4.85	~10.5
4	**402**	14/1/2002	2:07	Hakuho Maru	CPR	61.68	140.00	5.09	~10.5
4	**403**	14/1/2002	2:26	Hakuho Maru	CPR	61.59	140.00	4.86	~10.5
4	**404**	14/1/2002	2:46	Hakuho Maru	CPR	61.51	140.00	5.07	~10.5
4	**405**	14/1/2002	3:06	Hakuho Maru	CPR	61.42	140.00	5.10	~10.5
4	**406**	14/1/2002	3:25	Hakuho Maru	CPR	61.34	140.00	4.82	~10.5
4	**407**	14/1/2002	3:45	Hakuho Maru	CPR	61.26	140.00	5.04	~10.5
4	**408**	14/1/2002	4:05	Hakuho Maru	CPR	61.18	140.00	5.05	~10.5
4	**409**	14/1/2002	4:25	Hakuho Maru	CPR	61.09	140.00	5.04	~10.5
4	**410**	14/1/2002	4:46	Hakuho Maru	CPR	61.01	140.00	5.05	~10.5
4	**411**	14/1/2002	4:49	Hakuho Maru	CPR	61.00	140.00	0.34	~10.5
4	**412**	15/1/2002	16:43	Hakuho Maru	CPR	60.86	139.97	4.82	~10.5
4	**413**	15/1/2002	17:04	Hakuho Maru	CPR	60.78	139.99	5.18	~10.5
4	**414**	15/1/2002	17:24	Hakuho Maru	CPR	60.69	140.00	4.93	~10.5
4	**415**	15/1/2002	17:45	Hakuho Maru	CPR	60.61	140.00	5.00	~10.5
4	**416**	15/1/2002	18:06	Hakuho Maru	CPR	60.53	140.00	5.02	~10.5
4	**417**	15/1/2002	18:26	Hakuho Maru	CPR	60.45	140.01	4.84	~10.5
4	**418**	15/1/2002	18:47	Hakuho Maru	CPR	60.36	140.01	5.05	~10.5
4	**419**	15/1/2002	19:08	Hakuho Maru	CPR	60.28	140.01	5.01	~10.5
4	**420**	15/1/2002	19:29	Hakuho Maru	CPR	60.20	140.00	5.01	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
4	421	15/1/2002	19:50	Hakuho Maru	CPR	60.11	140.00	5.01	~10.5
4	422	15/1/2002	20:11	Hakuho Maru	CPR	60.03	140.00	5.01	~10.5
4	423	15/1/2002	20:18	Hakuho Maru	CPR	60.00	140.00	1.67	~10.5
4	424	17/1/2002	18:45	Hakuho Maru	CPR	54.62	139.97	4.88	~10.5
4	425	17/1/2002	19:10	Hakuho Maru	CPR	54.54	139.98	5.03	~10.5
4	426	17/1/2002	19:38	Hakuho Maru	CPR	54.46	139.99	5.01	~10.5
4	427	17/1/2002	19:58	Hakuho Maru	CPR	54.37	140.00	5.13	~10.5
4	428	17/1/2002	20:17	Hakuho Maru	CPR	54.29	140.00	4.98	~10.5
4	429	17/1/2002	20:36	Hakuho Maru	CPR	54.21	140.00	4.97	~10.5
4	430	17/1/2002	20:55	Hakuho Maru	CPR	54.12	140.00	4.94	~10.5
4	431	17/1/2002	21:14	Hakuho Maru	CPR	54.04	140.00	4.96	~10.5
4	432	17/1/2002	21:34	Hakuho Maru	CPR	53.95	140.00	5.24	~10.5
4	433	17/1/2002	21:53	Hakuho Maru	CPR	53.87	140.01	4.99	~10.5
4	434	17/1/2002	22:12	Hakuho Maru	CPR	53.79	140.00	4.99	~10.5
4	435	17/1/2002	22:31	Hakuho Maru	CPR	53.70	140.00	4.99	~10.5
4	436	17/1/2002	22:50	Hakuho Maru	CPR	53.62	140.00	4.95	~10.5
4	437	17/1/2002	23:10	Hakuho Maru	CPR	53.54	140.00	5.22	~10.5
4	438	17/1/2002	23:29	Hakuho Maru	CPR	53.45	140.00	5.01	~10.5
4	439	17/1/2002	23:48	Hakuho Maru	CPR	53.37	140.01	4.97	~10.5
4	440	18/1/2002	00:07	Hakuho Maru	CPR	53.29	140.01	4.88	~10.5
4	441	18/1/2002	00:27	Hakuho Maru	CPR	53.20	140.01	5.14	~10.5
4	442	18/1/2002	00:46	Hakuho Maru	CPR	53.12	140.00	4.88	~10.5
4	443	18/1/2002	01:06	Hakuho Maru	CPR	53.04	140.00	5.11	~10.5
4	444	18/1/2002	01:26	Hakuho Maru	CPR	52.95	140.00	5.09	~10.5
4	445	18/1/2002	01:46	Hakuho Maru	CPR	52.87	140.00	5.08	~10.5
4	446	18/1/2002	02:05	Hakuho Maru	CPR	52.79	140.00	4.87	~10.5
4	447	18/1/2002	02:25	Hakuho Maru	CPR	52.70	140.00	5.17	~10.5
4	448	18/1/2002	02:44	Hakuho Maru	CPR	52.62	140.00	4.94	~10.5
4	449	18/1/2002	03:03	Hakuho Maru	CPR	52.53	140.00	5.02	~10.5
4	450	18/1/2002	03:22	Hakuho Maru	CPR	52.45	140.01	4.98	~10.5
4	451	18/1/2002	03:41	Hakuho Maru	CPR	52.37	140.01	4.95	~10.5
4	452	18/1/2002	04:01	Hakuho Maru	CPR	52.28	140.01	5.22	~10.5
4	453	18/1/2002	04:20	Hakuho Maru	CPR	52.20	140.00	4.89	~10.5
4	454	18/1/2002	04:40	Hakuho Maru	CPR	52.11	140.00	5.16	~10.5
4	455	18/1/2002	04:59	Hakuho Maru	CPR	52.03	140.00	4.90	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
4	**456**	18/1/2002	05:18	Hakuho Maru	CPR	51.95	140.00	4.96	~10.5
4	**457**	18/1/2002	05:37	Hakuho Maru	CPR	51.87	140.00	4.98	~10.5
4	**458**	18/1/2002	05:57	Hakuho Maru	CPR	51.78	140.00	5.22	~10.5
4	**459**	18/1/2002	06:16	Hakuho Maru	CPR	51.70	140.00	5.02	~10.5
4	**460**	18/1/2002	06:35	Hakuho Maru	CPR	51.61	140.00	5.03	~10.5
4	**461**	18/1/2002	06:54	Hakuho Maru	CPR	51.53	140.00	4.93	~10.5
4	**462**	18/1/2002	07:13	Hakuho Maru	CPR	51.45	140.00	4.95	~10.5
4	**463**	18/1/2002	07:33	Hakuho Maru	CPR	51.36	140.00	5.22	~10.5
4	**464**	18/1/2002	07:52	Hakuho Maru	CPR	51.28	140.00	4.91	~10.5
4	**465**	18/1/2002	08:11	Hakuho Maru	CPR	51.20	140.00	4.89	~10.5
4	**466**	18/1/2002	08:31	Hakuho Maru	CPR	51.11	140.00	5.14	~10.5
4	**467**	18/1/2002	08:51	Hakuho Maru	CPR	51.03	139.99	5.11	~10.5
4	**468**	18/1/2002	09:10	Hakuho Maru	CPR	50.95	140.00	4.83	~10.5
4	**469**	18/1/2002	09:30	Hakuho Maru	CPR	50.86	140.00	5.11	~10.5
4	**470**	18/1/2002	09:50	Hakuho Maru	CPR	50.77	140.00	5.14	~10.5
4	**471**	18/1/2002	10:09	Hakuho Maru	CPR	50.69	140.00	4.91	~10.5
4	**472**	18/1/2002	10:28	Hakuho Maru	CPR	50.61	140.00	4.90	~10.5
4	**473**	18/1/2002	10:48	Hakuho Maru	CPR	50.52	140.00	5.18	~10.5
4	**474**	18/1/2002	11:07	Hakuho Maru	CPR	50.44	140.00	4.93	~10.5
4	**475**	18/1/2002	11:27	Hakuho Maru	CPR	50.36	140.00	5.18	~10.5
4	**476**	18/1/2002	11:46	Hakuho Maru	CPR	50.27	140.00	4.87	~10.5
4	**477**	18/1/2002	12:06	Hakuho Maru	CPR	50.19	140.00	5.14	~10.5
4	**478**	18/1/2002	12:25	Hakuho Maru	CPR	50.11	140.00	4.92	~10.5
4	**479**	18/1/2002	12:45	Hakuho Maru	CPR	50.02	140.03	5.17	~10.5
4	**480**	18/1/2002	19:18	Hakuho Maru	CPR	50.02	139.99	5.02	~10.5
4	**481**	18/1/2002	22:47	Hakuho Maru	CPR	49.99	139.95	5.03	~10.5
4	**482**	19/1/2002	00:55	Hakuho Maru	CPR	49.94	139.94	4.82	~10.5
4	**483**	19/1/2002	01:15	Hakuho Maru	CPR	49.85	139.96	4.99	~10.5
4	**484**	19/1/2002	01:35	Hakuho Maru	CPR	49.77	139.99	5.09	~10.5
4	**485**	19/1/2002	01:55	Hakuho Maru	CPR	49.69	140.00	5.04	~10.5
4	**486**	19/1/2002	02:15	Hakuho Maru	CPR	49.60	140.01	5.03	~10.5
4	**487**	19/1/2002	02:35	Hakuho Maru	CPR	49.52	140.01	5.01	~10.5
4	**488**	19/1/2002	02:55	Hakuho Maru	CPR	49.44	140.01	5.00	~10.5
4	**489**	19/1/2002	03:15	Hakuho Maru	CPR	49.35	140.01	5.00	~10.5
4	**490**	19/1/2002	03:35	Hakuho Maru	CPR	49.27	140.01	5.03	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
4	491	19/1/2002	03:55	Hakuho Maru	CPR	49.18	140.01	5.05	~10.5
4	492	19/1/2002	04:15	Hakuho Maru	CPR	49.10	140.01	5.11	~10.5
4	493	19/1/2002	04:34	Hakuho Maru	CPR	49.02	140.01	4.90	~10.5
4	494	19/1/2002	04:54	Hakuho Maru	CPR	48.93	140.00	5.10	~10.5
4	495	19/1/2002	05:14	Hakuho Maru	CPR	48.85	140.00	5.06	~10.5
4	496	19/1/2002	05:33	Hakuho Maru	CPR	48.77	140.00	4.83	~10.5
4	497	19/1/2002	05:53	Hakuho Maru	CPR	48.68	140.00	5.11	~10.5
4	498	19/1/2002	06:13	Hakuho Maru	CPR	48.60	140.00	5.15	~10.5
4	499	19/1/2002	06:32	Hakuho Maru	CPR	48.52	140.00	4.87	~10.5
4	500	19/1/2002	06:52	Hakuho Maru	CPR	48.43	140.00	5.13	~10.5
4	501	19/1/2002	07:11	Hakuho Maru	CPR	48.35	140.00	4.89	~10.5
4	502	19/1/2002	07:31	Hakuho Maru	CPR	48.26	140.00	5.09	~10.5
4	503	19/1/2002	07:51	Hakuho Maru	CPR	48.18	140.00	5.14	~10.5
4	504	19/1/2002	08:10	Hakuho Maru	CPR	48.10	140.00	4.94	~10.5
4	505	19/1/2002	08:29	Hakuho Maru	CPR	48.01	140.00	5.00	~10.5
4	506	19/1/2002	08:48	Hakuho Maru	CPR	47.93	140.01	5.00	~10.5
4	507	19/1/2002	09:07	Hakuho Maru	CPR	47.85	140.01	5.00	~10.5
4	508	19/1/2002	09:26	Hakuho Maru	CPR	47.76	140.01	5.02	~10.5
4	509	19/1/2002	09:45	Hakuho Maru	CPR	47.68	140.00	4.99	~10.5
4	510	19/1/2002	10:04	Hakuho Maru	CPR	47.60	140.00	4.97	~10.5
4	511	19/1/2002	10:23	Hakuho Maru	CPR	47.51	140.00	5.25	~10.5
4	512	19/1/2002	10:43	Hakuho Maru	CPR	47.43	140.00	4.92	~10.5
4	513	19/1/2002	11:02	Hakuho Maru	CPR	47.35	140.00	4.92	~10.5
4	514	19/1/2002	11:22	Hakuho Maru	CPR	47.26	140.00	5.18	~10.5
4	515	19/1/2002	11:41	Hakuho Maru	CPR	47.18	140.00	4.92	~10.5
4	516	19/1/2002	12:00	Hakuho Maru	CPR	47.09	140.00	4.95	~10.5
4	517	19/1/2002	12:24	Hakuho Maru	CPR	47.01	140.00	5.22	~10.5
5	518	7/2/2002	19:58	Tangaroa	CPR	-47.08	139.99	4.83	~10.5
5	519	7/2/2002	20:25	Tangaroa	CPR	-47.16	140.00	5.16	~10.5
5	520	7/2/2002	20:50	Tangaroa	CPR	-47.25	140.00	4.84	~10.5
5	521	7/2/2002	21:17	Tangaroa	CPR	-47.33	140.00	5.14	~10.5
5	522	7/2/2002	21:43	Tangaroa	CPR	-47.41	140.01	4.89	~10.5
5	523	7/2/2002	22:10	Tangaroa	CPR	-47.50	140.01	5.05	~10.5
5	524	7/2/2002	22:37	Tangaroa	CPR	-47.58	140.00	5.07	~10.5
5	525	7/2/2002	23:04	Tangaroa	CPR	-47.66	140.00	5.02	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**526**	7/2/2002	23:31	Tangaroa	CPR	-47.75	140.00	5.00	~10.5
5	**527**	7/2/2002	23:57	Tangaroa	CPR	-47.83	140.00	4.87	~10.5
5	**528**	8/2/2002	00:24	Tangaroa	CPR	-47.91	140.00	5.04	~10.5
5	**529**	8/2/2002	00:51	Tangaroa	CPR	-48.00	140.00	5.04	~10.5
5	**530**	8/2/2002	01:18	Tangaroa	CPR	-48.08	140.00	4.95	~10.5
5	**531**	8/2/2002	01:46	Tangaroa	CPR	-48.16	140.00	5.06	~10.5
5	**532**	8/2/2002	02:13	Tangaroa	CPR	-48.25	140.00	4.90	~10.5
5	**533**	8/2/2002	02:41	Tangaroa	CPR	-48.33	140.00	5.08	~10.5
5	**534**	8/2/2002	03:08	Tangaroa	CPR	-48.41	140.00	4.93	~10.5
5	**535**	8/2/2002	03:36	Tangaroa	CPR	-48.50	140.00	5.09	~10.5
5	**536**	8/2/2002	04:03	Tangaroa	CPR	-48.58	140.00	4.88	~10.5
5	**537**	8/2/2002	04:31	Tangaroa	CPR	-48.66	140.00	5.03	~10.5
5	**538**	8/2/2002	04:59	Tangaroa	CPR	-48.75	140.00	4.98	~10.5
5	**539**	8/2/2002	05:28	Tangaroa	CPR	-48.83	140.00	5.08	~10.5
5	**540**	8/2/2002	05:56	Tangaroa	CPR	-48.91	140.01	4.90	~10.5
5	**541**	8/2/2002	06:25	Tangaroa	CPR	-49.00	140.01	5.14	~10.5
5	**542**	8/2/2002	06:53	Tangaroa	CPR	-49.08	140.01	4.86	~10.5
5	**543**	8/2/2002	07:23	Tangaroa	CPR	-49.16	140.02	5.11	~10.5
5	**544**	8/2/2002	07:52	Tangaroa	CPR	-49.25	140.03	4.94	~10.5
5	**545**	8/2/2002	08:22	Tangaroa	CPR	-49.33	140.03	5.02	~10.5
5	**546**	8/2/2002	08:53	Tangaroa	CPR	-49.41	140.04	5.07	~10.5
5	**547**	8/2/2002	09:24	Tangaroa	CPR	-49.50	140.04	5.01	~10.5
5	**548**	8/2/2002	09:55	Tangaroa	CPR	-49.58	140.03	4.88	~10.5
5	**549**	8/2/2002	10:27	Tangaroa	CPR	-49.66	140.03	5.02	~10.5
5	**550**	8/2/2002	10:58	Tangaroa	CPR	-49.74	140.03	4.96	~10.5
5	**551**	8/2/2002	11:30	Tangaroa	CPR	-49.83	140.03	5.05	~10.5
5	**552**	8/2/2002	12:02	Tangaroa	CPR	-49.91	140.03	4.97	~10.5
5	**553**	8/2/2002	12:34	Tangaroa	CPR	-49.99	140.03	5.03	~10.5
5	**554**	8/2/2002	13:06	Tangaroa	CPR	-50.08	140.04	5.02	~10.5
5	**555**	8/2/2002	13:38	Tangaroa	CPR	-50.16	140.04	5.03	~10.5
5	**556**	8/2/2002	14:11	Tangaroa	CPR	-50.25	140.04	5.05	~10.5
5	**557**	8/2/2002	14:45	Tangaroa	CPR	-50.33	140.04	5.00	~10.5
5	**558**	8/2/2002	15:21	Tangaroa	CPR	-50.41	140.05	4.92	~10.5
5	**559**	8/2/2002	15:57	Tangaroa	CPR	-50.49	140.05	4.99	~10.5
5	**560**	8/2/2002	16:33	Tangaroa	CPR	-50.58	140.05	5.02	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	561	8/2/2002	17:08	Tangaroa	CPR	-50.66	140.04	5.08	~10.5
5	562	8/2/2002	17:42	Tangaroa	CPR	-50.74	140.03	4.92	~10.5
5	563	8/2/2002	18:17	Tangaroa	CPR	-50.83	140.01	5.06	~10.5
5	564	8/2/2002	18:52	Tangaroa	CPR	-50.91	140.00	5.01	~10.5
5	565	8/2/2002	19:24	Tangaroa	CPR	-50.99	139.98	4.87	~10.5
5	566	8/2/2002	19:57	Tangaroa	CPR	-51.07	139.96	5.01	~10.5
5	567	8/2/2002	20:30	Tangaroa	CPR	-51.16	139.95	5.08	~10.5
5	568	8/2/2002	20:59	Tangaroa	CPR	-51.24	139.94	5.03	~10.5
5	569	8/2/2002	21:27	Tangaroa	CPR	-51.32	139.94	4.93	~10.5
5	570	8/2/2002	21:55	Tangaroa	CPR	-51.41	139.94	4.94	~10.5
5	571	8/2/2002	22:24	Tangaroa	CPR	-51.49	139.94	5.05	~10.5
5	572	8/2/2002	22:53	Tangaroa	CPR	-51.57	139.94	5.01	~10.5
5	573	8/2/2002	23:22	Tangaroa	CPR	-51.66	139.94	5.01	~10.5
5	574	8/2/2002	23:51	Tangaroa	CPR	-51.74	139.95	5.05	~10.5
5	575	9/2/2002	00:20	Tangaroa	CPR	-51.82	139.96	4.89	~10.5
5	576	9/2/2002	00:50	Tangaroa	CPR	-51.91	139.97	5.01	~10.5
5	577	9/2/2002	01:21	Tangaroa	CPR	-51.99	139.98	5.12	~10.5
5	578	9/2/2002	01:51	Tangaroa	CPR	-52.07	139.99	4.95	~10.5
5	579	9/2/2002	02:21	Tangaroa	CPR	-52.16	140.00	5.00	~10.5
5	580	9/2/2002	02:51	Tangaroa	CPR	-52.24	140.01	4.99	~10.5
5	581	9/2/2002	03:21	Tangaroa	CPR	-52.32	140.02	4.97	~10.5
5	582	9/2/2002	03:51	Tangaroa	CPR	-52.40	140.03	5.00	~10.5
5	583	9/2/2002	04:21	Tangaroa	CPR	-52.49	140.03	4.97	~10.5
5	584	9/2/2002	04:51	Tangaroa	CPR	-52.57	140.03	5.03	~10.5
5	585	9/2/2002	05:21	Tangaroa	CPR	-52.66	140.02	5.10	~10.5
5	586	9/2/2002	05:50	Tangaroa	CPR	-52.74	140.02	4.96	~10.5
5	587	9/2/2002	06:19	Tangaroa	CPR	-52.82	140.02	4.99	~10.5
5	588	9/2/2002	06:47	Tangaroa	CPR	-52.90	140.01	4.91	~10.5
5	589	9/2/2002	07:15	Tangaroa	CPR	-52.99	140.01	4.99	~10.5
5	590	9/2/2002	07:44	Tangaroa	CPR	-53.07	140.00	5.12	~10.5
5	591	9/2/2002	08:12	Tangaroa	CPR	-53.15	140.00	4.97	~10.5
5	592	9/2/2002	08:40	Tangaroa	CPR	-53.24	139.99	4.95	~10.5
5	593	9/2/2002	09:09	Tangaroa	CPR	-53.32	139.99	5.12	~10.5
5	594	9/2/2002	09:36	Tangaroa	CPR	-53.40	139.98	4.85	~10.5
5	595	9/2/2002	10:04	Tangaroa	CPR	-53.49	139.99	5.00	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	596	9/2/2002	10:33	Tangaroa	CPR	-53.57	139.99	5.02	~10.5
5	597	9/2/2002	11:03	Tangaroa	CPR	-53.65	140.00	5.10	~10.5
5	598	9/2/2002	11:32	Tangaroa	CPR	-53.74	140.00	4.89	~10.5
5	599	9/2/2002	12:03	Tangaroa	CPR	-53.82	140.01	5.10	~10.5
5	600	9/2/2002	12:34	Tangaroa	CPR	-53.90	140.01	5.03	~10.5
5	601	9/2/2002	13:05	Tangaroa	CPR	-53.99	140.01	4.95	~10.5
5	602	11/2/2002	5:21	Tangaroa	CPR	-61.12	140.00	4.96	~10.5
5	603	11/2/2002	5:48	Tangaroa	CPR	-61.20	140.00	4.89	~10.5
5	604	11/2/2002	6:16	Tangaroa	CPR	-61.29	140.00	5.07	~10.5
5	605	11/2/2002	6:43	Tangaroa	CPR	-61.37	140.00	4.93	~10.5
5	606	11/2/2002	7:11	Tangaroa	CPR	-61.46	140.00	5.12	~10.5
5	607	11/2/2002	7:38	Tangaroa	CPR	-61.54	139.99	4.95	~10.5
5	608	11/2/2002	8:05	Tangaroa	CPR	-61.62	139.99	5.00	~10.5
5	609	11/2/2002	8:32	Tangaroa	CPR	-61.70	139.98	5.00	~10.5
5	610	11/2/2002	8:59	Tangaroa	CPR	-61.79	139.98	5.02	~10.5
5	611	11/2/2002	9:26	Tangaroa	CPR	-61.87	139.98	5.02	~10.5
5	612	11/2/2002	9:52	Tangaroa	CPR	-61.95	139.98	4.90	~10.5
5	613	11/2/2002	10:19	Tangaroa	CPR	-62.04	139.99	5.11	~10.5
5	614	11/2/2002	10:45	Tangaroa	CPR	-62.12	139.99	4.93	~10.5
5	615	11/2/2002	11:11	Tangaroa	CPR	-62.20	140.00	4.99	~10.5
5	616	11/2/2002	11:37	Tangaroa	CPR	-62.29	140.00	5.00	~10.5
5	617	11/2/2002	12:03	Tangaroa	CPR	-62.37	140.01	5.01	~10.5
5	618	11/2/2002	12:28	Tangaroa	CPR	-62.45	140.00	4.91	~10.5
5	619	11/2/2002	12:54	Tangaroa	CPR	-62.54	140.00	5.15	~10.5
5	620	11/2/2002	13:19	Tangaroa	CPR	-62.62	140.00	5.01	~10.5
5	621	11/2/2002	13:44	Tangaroa	CPR	-62.70	140.00	4.99	~10.5
5	622	11/2/2002	14:09	Tangaroa	CPR	-62.79	140.00	4.95	~10.5
5	623	11/2/2002	14:34	Tangaroa	CPR	-62.87	140.00	4.93	~10.5
5	624	11/2/2002	15:00	Tangaroa	CPR	-62.95	140.00	5.12	~10.5
5	625	11/2/2002	15:26	Tangaroa	CPR	-63.04	140.00	4.96	~10.5
5	626	11/2/2002	15:52	Tangaroa	CPR	-63.12	140.00	4.99	~10.5
5	627	11/2/2002	16:18	Tangaroa	CPR	-63.20	140.00	5.05	~10.5
5	628	11/2/2002	16:44	Tangaroa	CPR	-63.29	140.00	5.00	~10.5
5	629	11/2/2002	17:10	Tangaroa	CPR	-63.37	140.00	4.99	~10.5
5	630	11/2/2002	17:35	Tangaroa	CPR	-63.45	140.01	4.89	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**631**	11/2/2002	18:01	Tangaroa	CPR	-63.54	140.01	5.13	~10.5
5	**632**	11/2/2002	18:27	Tangaroa	CPR	-63.62	140.01	5.01	~10.5
5	**633**	11/2/2002	18:52	Tangaroa	CPR	-63.70	140.00	4.84	~10.5
5	**634**	11/2/2002	19:17	Tangaroa	CPR	-63.79	140.00	5.09	~10.5
5	**635**	11/2/2002	19:41	Tangaroa	CPR	-63.87	139.99	4.90	~10.5
5	**636**	11/2/2002	20:07	Tangaroa	CPR	-63.95	139.98	5.12	~10.5
5	**637**	11/2/2002	20:32	Tangaroa	CPR	-64.04	139.98	4.98	~10.5
5	**638**	11/2/2002	20:57	Tangaroa	CPR	-64.12	139.99	5.04	~10.5
5	**639**	11/2/2002	21:21	Tangaroa	CPR	-64.20	140.01	4.85	~10.5
5	**640**	11/2/2002	21:46	Tangaroa	CPR	-64.29	140.01	5.07	~10.5
5	**641**	11/2/2002	22:11	Tangaroa	CPR	-64.37	140.01	5.01	~10.5
5	**642**	11/2/2002	22:36	Tangaroa	CPR	-64.45	140.01	4.98	~10.5
5	**643**	11/2/2002	23:01	Tangaroa	CPR	-64.54	140.01	4.97	~10.5
5	**644**	11/2/2002	23:26	Tangaroa	CPR	-64.62	140.01	5.02	~10.5
5	**645**	11/2/2002	23:51	Tangaroa	CPR	-64.70	140.00	5.00	~10.5
5	**646**	12/2/2002	0:17	Tangaroa	CPR	-64.79	139.99	5.14	~10.5
5	**647**	12/2/2002	0:42	Tangaroa	CPR	-64.87	139.99	5.00	~10.5
5	**648**	12/2/2002	1:07	Tangaroa	CPR	-64.95	139.99	4.96	~10.5
5	**649**	12/2/2002	1:32	Tangaroa	CPR	-65.04	139.99	4.95	~10.5
5	**650**	12/2/2002	1:57	Tangaroa	CPR	-65.12	139.99	5.03	~10.5
5	**651**	12/2/2002	2:21	Tangaroa	CPR	-65.20	140.00	4.88	~10.5
5	**652**	12/2/2002	2:46	Tangaroa	CPR	-65.29	140.00	5.13	~10.5
5	**653**	12/2/2002	3:10	Tangaroa	CPR	-65.37	139.99	4.92	~10.5
5	**654**	12/2/2002	3:35	Tangaroa	CPR	-65.45	139.99	5.16	~10.5
5	**655**	12/2/2002	3:59	Tangaroa	CPR	-65.54	140.01	4.95	~10.5
5	**656**	12/2/2002	4:27	Tangaroa	CPR	-65.62	140.00	4.96	~10.5
5	**657**	12/2/2002	4:55	Tangaroa	CPR	-65.70	139.98	5.03	~10.5
5	**658**	12/2/2002	5:21	Tangaroa	CPR	-65.79	139.99	5.06	~10.5
5	**659**	12/2/2002	5:47	Tangaroa	CPR	-65.87	140.00	5.00	~10.5
5	**660**	12/2/2002	6:12	Tangaroa	CPR	-65.95	139.99	4.84	~10.5
5	**661**	12/2/2002	6:38	Tangaroa	CPR	-66.03	139.98	5.07	~10.5
5	**662**	12/2/2002	7:07	Tangaroa	CPR	-66.11	139.97	4.96	~10.5
5	**663**	12/2/2002	7:40	Tangaroa	CPR	-66.19	140.00	5.07	~10.5
5	**664**	12/2/2002	7:59	Tangaroa	CPR	-66.24	139.98	2.67	~10.5
5	**665**	19/2/2002	6:56	Tangaroa	CPR	-64.67	139.88	4.86	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**666**	19/2/2002	7:28	Tangaroa	CPR	-64.59	139.90	5.13	~10.5
5	**667**	19/2/2002	7:55	Tangaroa	CPR	-64.50	139.91	4.87	~10.5
5	**668**	19/2/2002	8:23	Tangaroa	CPR	-64.42	139.92	5.01	~10.5
5	**669**	19/2/2002	8:52	Tangaroa	CPR	-64.34	139.93	5.00	~10.5
5	**670**	19/2/2002	9:21	Tangaroa	CPR	-64.25	139.94	5.10	~10.5
5	**671**	19/2/2002	9:49	Tangaroa	CPR	-64.17	139.95	4.88	~10.5
5	**672**	19/2/2002	10:18	Tangaroa	CPR	-64.09	139.96	5.03	~10.5
5	**673**	19/2/2002	10:41	Tangaroa	CPR	-64.04	139.97	3.05	~10.5
5	**674**	19/2/2002	21:26	Tangaroa	CPR	-63.86	139.89	5.00	~10.5
5	**675**	19/2/2002	22:02	Tangaroa	CPR	-63.77	139.90	5.24	~10.5
5	**676**	19/2/2002	22:37	Tangaroa	CPR	-63.69	139.91	5.17	~10.5
5	**677**	19/2/2002	23:11	Tangaroa	CPR	-63.60	139.92	5.11	~10.5
5	**678**	19/2/2002	23:44	Tangaroa	CPR	-63.52	139.94	5.06	~10.5
5	**679**	20/2/2002	0:17	Tangaroa	CPR	-63.43	139.96	5.18	~10.5
5	**680**	20/2/2002	0:49	Tangaroa	CPR	-63.35	139.99	5.11	~10.5
5	**681**	20/2/2002	1:20	Tangaroa	CPR	-63.26	140.00	5.26	~10.5
5	**682**	20/2/2002	12:29	Tangaroa	CPR	-63.14	140.01	4.97	~10.5
5	**683**	20/2/2002	13:11	Tangaroa	CPR	-63.06	140.02	4.97	~10.5
5	**684**	20/2/2002	13:53	Tangaroa	CPR	-62.97	140.02	5.12	~10.5
5	**685**	20/2/2002	14:33	Tangaroa	CPR	-62.89	140.01	4.96	~10.5
5	**686**	20/2/2002	15:11	Tangaroa	CPR	-62.81	139.99	5.04	~10.5
5	**687**	20/2/2002	15:48	Tangaroa	CPR	-62.72	139.98	5.05	~10.5
5	**688**	20/2/2002	16:28	Tangaroa	CPR	-62.64	139.99	5.09	~10.5
5	**689**	20/2/2002	17:07	Tangaroa	CPR	-62.56	140.00	4.95	~10.5
5	**690**	20/2/2002	17:53	Tangaroa	CPR	-62.48	140.01	5.10	~10.5
5	**691**	21/2/2002	9:58	Tangaroa	CPR	-62.46	140.02	4.99	~10.5
5	**692**	21/2/2002	10:45	Tangaroa	CPR	-62.38	140.01	4.94	~10.5
5	**693**	21/2/2002	11:32	Tangaroa	CPR	-62.30	140.01	5.00	~10.5
5	**694**	21/2/2002	12:14	Tangaroa	CPR	-62.21	140.01	5.00	~10.5
5	**695**	21/2/2002	12:54	Tangaroa	CPR	-62.13	140.01	5.06	~10.5
5	**696**	21/2/2002	13:30	Tangaroa	CPR	-62.05	140.02	4.93	~10.5
5	**697**	21/2/2002	14:06	Tangaroa	CPR	-61.96	140.02	4.97	~10.5
5	**698**	21/2/2002	14:43	Tangaroa	CPR	-61.88	140.01	5.02	~10.5
5	**699**	21/2/2002	15:20	Tangaroa	CPR	-61.80	140.00	5.07	~10.5
5	**700**	21/2/2002	15:44	Tangaroa	CPR	-61.75	140.00	2.82	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	701	22/2/2002	8:37	Tangaroa	CPR	-61.66	140.02	4.87	~10.5
5	702	22/2/2002	9:13	Tangaroa	CPR	-61.58	140.01	5.08	~10.5
5	703	22/2/2002	9:48	Tangaroa	CPR	-61.49	140.01	4.93	~10.5
5	704	22/2/2002	10:24	Tangaroa	CPR	-61.41	140.01	5.02	~10.5
5	705	22/2/2002	11:00	Tangaroa	CPR	-61.33	140.01	4.97	~10.5
5	706	22/2/2002	11:37	Tangaroa	CPR	-61.24	140.01	5.06	~10.5
5	707	22/2/2002	12:14	Tangaroa	CPR	-61.16	140.01	5.04	~10.5
5	708	22/2/2002	12:51	Tangaroa	CPR	-61.08	140.01	5.02	~10.5
5	709	22/2/2002	13:24	Tangaroa	CPR	-61.00	140.00	4.39	~10.5
5	710	25/2/2002	4:56	Tangaroa	CPR	-66.36	139.90	4.99	~10.5
5	711	25/2/2002	5:20	Tangaroa	CPR	-66.29	139.80	4.94	~10.5
5	712	25/2/2002	5:45	Tangaroa	CPR	-66.22	139.71	5.02	~10.5
5	713	25/2/2002	6:11	Tangaroa	CPR	-66.14	139.65	5.00	~10.5
5	714	25/2/2002	6:36	Tangaroa	CPR	-66.06	139.61	4.87	~10.5
5	715	25/2/2002	7:02	Tangaroa	CPR	-65.98	139.57	5.07	~10.5
5	716	25/2/2002	7:28	Tangaroa	CPR	-65.89	139.56	5.02	~10.5
5	717	25/2/2002	7:54	Tangaroa	CPR	-65.81	139.55	5.05	~10.5
5	718	25/2/2002	8:19	Tangaroa	CPR	-65.73	139.50	4.88	~10.5
5	719	25/2/2002	8:45	Tangaroa	CPR	-65.65	139.49	5.09	~10.5
5	720	25/2/2002	9:11	Tangaroa	CPR	-65.56	139.49	4.93	~10.5
5	721	25/2/2002	9:39	Tangaroa	CPR	-65.48	139.48	4.99	~10.5
5	722	25/2/2002	10:08	Tangaroa	CPR	-65.40	139.54	5.15	~10.5
5	723	25/2/2002	10:36	Tangaroa	CPR	-65.32	139.55	4.94	~10.5
5	724	25/2/2002	11:06	Tangaroa	CPR	-65.23	139.54	4.99	~10.5
5	725	25/2/2002	11:36	Tangaroa	CPR	-65.15	139.54	4.91	~10.5
5	726	25/2/2002	12:07	Tangaroa	CPR	-65.07	139.54	5.13	~10.5
5	727	25/2/2002	12:36	Tangaroa	CPR	-64.99	139.56	4.93	~10.5
5	728	25/2/2002	13:05	Tangaroa	CPR	-64.90	139.60	4.95	~10.5
5	729	25/2/2002	13:33	Tangaroa	CPR	-64.82	139.64	4.99	~10.5
5	730	25/2/2002	14:02	Tangaroa	CPR	-64.74	139.67	5.13	~10.5
5	731	25/2/2002	14:30	Tangaroa	CPR	-64.66	139.72	5.02	~10.5
5	732	25/2/2002	14:58	Tangaroa	CPR	-64.58	139.78	4.97	~10.5
5	733	25/2/2002	15:26	Tangaroa	CPR	-64.50	139.83	4.97	~10.5
5	734	25/2/2002	15:54	Tangaroa	CPR	-64.42	139.88	5.00	~10.5
5	735	25/2/2002	16:22	Tangaroa	CPR	-64.34	139.93	5.01	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**736**	25/2/2002	16:49	Tangaroa	CPR	-64.26	139.96	5.05	~10.5
5	**737**	25/2/2002	17:15	Tangaroa	CPR	-64.17	139.98	4.92	~10.5
5	**738**	25/2/2002	17:42	Tangaroa	CPR	-64.09	139.98	5.03	~10.5
5	**739**	25/2/2002	18:09	Tangaroa	CPR	-64.01	139.98	4.99	~10.5
5	**740**	25/2/2002	18:36	Tangaroa	CPR	-63.92	139.97	4.95	~10.5
5	**741**	25/2/2002	19:13	Tangaroa	CPR	-63.84	139.97	5.10	~10.5
5	**742**	25/2/2002	19:57	Tangaroa	CPR	-63.76	139.99	4.90	~10.5
5	**743**	25/2/2002	20:22	Tangaroa	CPR	-63.67	140.00	5.11	~10.5
5	**744**	25/2/2002	21:00	Tangaroa	CPR	-63.59	140.01	4.99	~10.5
5	**745**	25/2/2002	21:54	Tangaroa	CPR	-63.51	140.01	4.98	~10.5
5	**746**	25/2/2002	22:27	Tangaroa	CPR	-63.42	140.01	4.97	~10.5
5	**747**	25/2/2002	22:51	Tangaroa	CPR	-63.34	140.00	4.92	~10.5
5	**748**	25/2/2002	23:15	Tangaroa	CPR	-63.26	140.00	5.04	~10.5
5	**749**	25/2/2002	23:39	Tangaroa	CPR	-63.18	140.00	5.01	~10.5
5	**750**	26/2/2002	0:12	Tangaroa	CPR	-63.09	140.00	5.06	~10.5
5	**751**	26/2/2002	0:44	Tangaroa	CPR	-63.01	140.00	4.88	~10.5
5	**752**	26/2/2002	1:10	Tangaroa	CPR	-62.93	140.00	4.97	~10.5
5	**753**	26/2/2002	1:35	Tangaroa	CPR	-62.84	140.00	5.16	~10.5
5	**754**	26/2/2002	2:00	Tangaroa	CPR	-62.76	140.00	4.85	~10.5
5	**755**	26/2/2002	2:27	Tangaroa	CPR	-62.67	139.99	5.11	~10.5
5	**756**	26/2/2002	2:53	Tangaroa	CPR	-62.59	139.99	4.88	~10.5
5	**757**	26/2/2002	3:20	Tangaroa	CPR	-62.51	140.00	5.03	~10.5
5	**758**	26/2/2002	3:47	Tangaroa	CPR	-62.43	140.00	4.99	~10.5
5	**759**	26/2/2002	4:14	Tangaroa	CPR	-62.34	140.00	5.01	~10.5
5	**760**	26/2/2002	4:40	Tangaroa	CPR	-62.26	140.01	4.98	~10.5
5	**761**	26/2/2002	5:08	Tangaroa	CPR	-62.17	140.01	5.12	~10.5
5	**762**	26/2/2002	5:38	Tangaroa	CPR	-62.09	140.01	4.99	~10.5
5	**763**	26/2/2002	6:09	Tangaroa	CPR	-62.01	140.01	4.91	~10.5
5	**764**	26/2/2002	6:41	Tangaroa	CPR	-61.93	140.02	4.98	~10.5
5	**765**	26/2/2002	7:14	Tangaroa	CPR	-61.84	140.02	5.05	~10.5
5	**766**	26/2/2002	7:47	Tangaroa	CPR	-61.76	140.02	5.07	~10.5
5	**767**	26/2/2002	8:19	Tangaroa	CPR	-61.68	140.03	4.97	~10.5
5	**768**	26/2/2002	8:51	Tangaroa	CPR	-61.59	140.06	5.01	~10.5
5	**769**	26/2/2002	9:23	Tangaroa	CPR	-61.51	140.08	4.96	~10.5
5	**770**	26/2/2002	9:55	Tangaroa	CPR	-61.43	140.10	4.99	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**771**	26/2/2002	10:28	Tangaroa	CPR	-61.34	140.12	5.09	~10.5
5	**772**	26/2/2002	11:01	Tangaroa	CPR	-61.26	140.10	4.94	~10.5
5	**773**	26/2/2002	11:34	Tangaroa	CPR	-61.18	140.07	4.93	~10.5
5	**774**	26/2/2002	12:08	Tangaroa	CPR	-61.10	140.05	5.02	~10.5
5	**775**	26/2/2002	12:42	Tangaroa	CPR	-61.02	140.03	5.03	~10.5
5	**776**	26/2/2002	13:16	Tangaroa	CPR	-60.93	140.01	4.99	~10.5
5	**777**	26/2/2002	13:50	Tangaroa	CPR	-60.85	140.00	4.97	~10.5
5	**778**	26/2/2002	14:24	Tangaroa	CPR	-60.77	140.00	5.05	~10.5
5	**779**	26/2/2002	14:58	Tangaroa	CPR	-60.68	140.00	5.00	~10.5
5	**780**	26/2/2002	15:32	Tangaroa	CPR	-60.60	140.01	5.03	~10.5
5	**781**	26/2/2002	16:06	Tangaroa	CPR	-60.52	140.00	5.01	~10.5
5	**782**	26/2/2002	16:40	Tangaroa	CPR	-60.43	139.98	4.96	~10.5
5	**783**	26/2/2002	17:14	Tangaroa	CPR	-60.35	139.97	5.05	~10.5
5	**784**	26/2/2002	17:47	Tangaroa	CPR	-60.27	139.95	4.96	~10.5
5	**785**	26/2/2002	18:19	Tangaroa	CPR	-60.19	139.93	4.93	~10.5
5	**786**	26/2/2002	18:51	Tangaroa	CPR	-60.10	139.91	5.06	~10.5
5	**787**	26/2/2002	19:22	Tangaroa	CPR	-60.03	139.94	4.98	~10.5
5	**788**	26/2/2002	19:56	Tangaroa	CPR	-59.98	140.07	5.07	~10.5
5	**789**	26/2/2002	20:25	Tangaroa	CPR	-59.99	140.03	1.69	~10.5
5	**790**	27/2/2002	5:14	Tangaroa	CPR	-59.92	140.01	4.83	~10.5
5	**791**	27/2/2002	5:40	Tangaroa	CPR	-59.84	140.01	4.98	~10.5
5	**792**	27/2/2002	6:07	Tangaroa	CPR	-59.75	140.02	5.19	~10.5
5	**793**	27/2/2002	6:32	Tangaroa	CPR	-59.67	140.03	4.82	~10.5
5	**794**	27/2/2002	6:58	Tangaroa	CPR	-59.59	140.04	5.03	~10.5
5	**795**	27/2/2002	7:24	Tangaroa	CPR	-59.50	140.04	5.06	~10.5
5	**796**	27/2/2002	7:50	Tangaroa	CPR	-59.42	140.05	5.05	~10.5
5	**797**	27/2/2002	8:16	Tangaroa	CPR	-59.34	140.04	5.00	~10.5
5	**798**	27/2/2002	8:42	Tangaroa	CPR	-59.25	140.04	4.97	~10.5
5	**799**	27/2/2002	9:08	Tangaroa	CPR	-59.17	140.04	4.94	~10.5
5	**800**	27/2/2002	9:35	Tangaroa	CPR	-59.09	140.03	5.05	~10.5
5	**801**	27/2/2002	10:02	Tangaroa	CPR	-59.00	140.02	5.01	~10.5
5	**802**	27/2/2002	10:29	Tangaroa	CPR	-58.92	140.01	5.03	~10.5
5	**803**	27/2/2002	10:56	Tangaroa	CPR	-58.84	140.00	5.02	~10.5
5	**804**	27/2/2002	11:22	Tangaroa	CPR	-58.76	140.00	4.84	~10.5
5	**805**	27/2/2002	11:49	Tangaroa	CPR	-58.67	139.99	5.01	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	806	27/2/2002	12:16	Tangaroa	CPR	-58.59	139.99	5.04	~10.5
5	807	27/2/2002	12:43	Tangaroa	CPR	-58.50	139.99	5.05	~10.5
5	808	27/2/2002	13:10	Tangaroa	CPR	-58.42	139.99	4.99	~10.5
5	809	27/2/2002	13:37	Tangaroa	CPR	-58.34	139.99	5.00	~10.5
5	810	27/2/2002	14:04	Tangaroa	CPR	-58.25	140.00	5.04	~10.5
5	811	27/2/2002	14:31	Tangaroa	CPR	-58.17	140.00	4.98	~10.5
5	812	27/2/2002	14:58	Tangaroa	CPR	-58.09	140.00	4.99	~10.5
5	813	27/2/2002	15:25	Tangaroa	CPR	-58.00	140.00	5.02	~10.5
5	814	27/2/2002	15:52	Tangaroa	CPR	-57.92	140.00	5.04	~10.5
5	815	27/2/2002	16:18	Tangaroa	CPR	-57.84	140.00	4.85	~10.5
5	816	27/2/2002	16:45	Tangaroa	CPR	-57.75	140.00	5.03	~10.5
5	817	27/2/2002	17:12	Tangaroa	CPR	-57.67	140.00	5.06	~10.5
5	818	27/2/2002	17:38	Tangaroa	CPR	-57.59	140.00	4.91	~10.5
5	819	27/2/2002	18:05	Tangaroa	CPR	-57.50	140.00	5.09	~10.5
5	820	27/2/2002	18:31	Tangaroa	CPR	-57.42	140.01	4.95	~10.5
5	821	27/2/2002	18:58	Tangaroa	CPR	-57.34	140.01	5.11	~10.5
5	822	27/2/2002	19:24	Tangaroa	CPR	-57.25	140.01	4.93	~10.5
5	823	27/2/2002	19:51	Tangaroa	CPR	-57.17	140.01	5.08	~10.5
5	824	27/2/2002	20:17	Tangaroa	CPR	-57.09	140.00	4.88	~10.5
5	825	27/2/2002	20:35	Tangaroa	CPR	-57.04	140.00	3.08	~10.5
5	826	28/2/2002	21:36	Tangaroa	CPR	-56.85	139.93	4.89	~10.5
5	827	28/2/2002	22:17	Tangaroa	CPR	-56.76	139.94	5.10	~10.5
5	828	28/2/2002	22:57	Tangaroa	CPR	-56.68	139.96	4.93	~10.5
5	829	28/2/2002	23:38	Tangaroa	CPR	-56.60	139.97	4.98	~10.5
5	830	1/3/2002	0:21	Tangaroa	CPR	-56.52	139.99	5.06	~10.5
5	831	1/3/2002	1:03	Tangaroa	CPR	-56.43	140.00	4.96	~10.5
5	832	1/3/2002	1:48	Tangaroa	CPR	-56.35	140.02	5.08	~10.5
5	833	1/3/2002	2:32	Tangaroa	CPR	-56.27	140.04	4.94	~10.5
5	834	1/3/2002	3:16	Tangaroa	CPR	-56.18	140.05	5.06	~10.5
5	835	1/3/2002	4:01	Tangaroa	CPR	-56.10	140.07	4.99	~10.5
5	836	1/3/2002	4:46	Tangaroa	CPR	-56.02	140.08	4.94	~10.5
5	837	1/3/2002	5:31	Tangaroa	CPR	-55.94	140.09	5.07	~10.5
5	838	1/3/2002	6:14	Tangaroa	CPR	-55.85	140.10	5.00	~10.5
5	839	1/3/2002	6:59	Tangaroa	CPR	-55.77	140.11	4.99	~10.5
5	840	1/3/2002	7:43	Tangaroa	CPR	-55.69	140.12	4.97	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	841	1/3/2002	8:24	Tangaroa	CPR	-55.60	140.13	4.98	~10.5
5	842	1/3/2002	9:04	Tangaroa	CPR	-55.52	140.14	5.02	~10.5
5	843	1/3/2002	9:43	Tangaroa	CPR	-55.44	140.16	4.97	~10.5
5	844	1/3/2002	10:22	Tangaroa	CPR	-55.35	140.18	5.07	~10.5
5	845	1/3/2002	10:59	Tangaroa	CPR	-55.27	140.19	4.94	~10.5
5	846	1/3/2002	11:36	Tangaroa	CPR	-55.19	140.20	5.04	~10.5
5	847	1/3/2002	12:12	Tangaroa	CPR	-55.11	140.21	4.91	~10.5
5	848	1/3/2002	12:49	Tangaroa	CPR	-55.02	140.22	5.10	~10.5
5	849	1/3/2002	13:23	Tangaroa	CPR	-54.94	140.22	5.03	~10.5
5	850	1/3/2002	13:49	Tangaroa	CPR	-54.86	140.21	4.87	~10.5
5	851	1/3/2002	14:18	Tangaroa	CPR	-54.77	140.20	5.08	~10.5
5	852	1/3/2002	14:47	Tangaroa	CPR	-54.69	140.19	4.92	~10.5
5	853	1/3/2002	15:17	Tangaroa	CPR	-54.61	140.18	5.09	~10.5
5	854	1/3/2002	15:47	Tangaroa	CPR	-54.52	140.17	5.03	~10.5
5	855	1/3/2002	16:16	Tangaroa	CPR	-54.44	140.15	4.85	~10.5
5	856	1/3/2002	16:47	Tangaroa	CPR	-54.36	140.13	5.11	~10.5
5	857	1/3/2002	17:17	Tangaroa	CPR	-54.28	140.12	4.99	~10.5
5	858	1/3/2002	17:47	Tangaroa	CPR	-54.20	140.09	4.94	~10.5
5	859	1/3/2002	18:17	Tangaroa	CPR	-54.12	140.05	4.96	~10.5
5	860	1/3/2002	18:48	Tangaroa	CPR	-54.03	140.01	5.16	~10.5
5	861	1/3/2002	19:02	Tangaroa	CPR	-54.00	139.99	2.05	~10.5
5	862	2/3/2002	02:41	Tangaroa	CPR	-53.92	140.00	4.64	~10.5
5	863	2/3/2002	03:06	Tangaroa	CPR	-53.84	140.00	4.71	~10.5
5	864	2/3/2002	03:31	Tangaroa	CPR	-53.77	140.00	4.74	~10.5
5	865	2/3/2002	03:56	Tangaroa	CPR	-53.69	140.00	4.72	~10.5
5	866	2/3/2002	04:21	Tangaroa	CPR	-53.61	140.00	4.71	~10.5
5	867	2/3/2002	04:46	Tangaroa	CPR	-53.53	140.00	4.78	~10.5
5	868	2/3/2002	05:11	Tangaroa	CPR	-53.45	140.00	4.76	~10.5
5	869	2/3/2002	05:35	Tangaroa	CPR	-53.37	139.99	4.56	~10.5
5	870	2/3/2002	06:00	Tangaroa	CPR	-53.29	139.99	4.78	~10.5
5	871	2/3/2002	06:25	Tangaroa	CPR	-53.21	139.99	4.80	~10.5
5	872	2/3/2002	06:49	Tangaroa	CPR	-53.14	139.98	4.58	~10.5
5	873	2/3/2002	07:14	Tangaroa	CPR	-53.06	139.98	4.73	~10.5
5	874	2/3/2002	07:39	Tangaroa	CPR	-52.98	139.98	4.85	~10.5
5	875	2/3/2002	08:03	Tangaroa	CPR	-52.90	139.98	4.66	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	876	2/3/2002	08:27	Tangaroa	CPR	-52.82	139.98	4.71	~10.5
5	877	2/3/2002	08:51	Tangaroa	CPR	-52.74	139.98	4.83	~10.5
5	878	2/3/2002	09:14	Tangaroa	CPR	-52.66	139.98	4.58	~10.5
5	879	2/3/2002	09:38	Tangaroa	CPR	-52.59	139.98	4.76	~10.5
5	880	2/3/2002	10:02	Tangaroa	CPR	-52.51	139.98	4.78	~10.5
5	881	2/3/2002	10:26	Tangaroa	CPR	-52.43	139.97	4.69	~10.5
5	882	2/3/2002	10:50	Tangaroa	CPR	-52.35	139.97	4.64	~10.5
5	883	2/3/2002	11:15	Tangaroa	CPR	-52.27	139.97	4.80	~10.5
5	884	2/3/2002	11:40	Tangaroa	CPR	-52.19	139.98	4.80	~10.5
5	885	2/3/2002	12:04	Tangaroa	CPR	-52.11	139.98	4.61	~10.5
5	886	2/3/2002	12:29	Tangaroa	CPR	-52.03	139.99	4.79	~10.5
5	887	2/3/2002	12:53	Tangaroa	CPR	-51.96	140.00	4.61	~10.5
5	888	2/3/2002	13:18	Tangaroa	CPR	-51.88	140.00	4.80	~10.5
5	889	2/3/2002	13:43	Tangaroa	CPR	-51.80	140.00	4.81	~10.5
5	890	2/3/2002	14:07	Tangaroa	CPR	-51.72	140.00	4.58	~10.5
5	891	2/3/2002	14:33	Tangaroa	CPR	-51.64	140.00	4.83	~10.5
5	892	2/3/2002	14:58	Tangaroa	CPR	-51.56	140.00	4.67	~10.5
5	893	2/3/2002	15:24	Tangaroa	CPR	-51.48	140.00	4.78	~10.5
5	894	2/3/2002	15:50	Tangaroa	CPR	-51.40	140.00	4.77	~10.5
5	895	2/3/2002	16:15	Tangaroa	CPR	-51.33	140.00	4.57	~10.5
5	896	2/3/2002	16:41	Tangaroa	CPR	-51.25	140.00	4.75	~10.5
5	897	2/3/2002	17:07	Tangaroa	CPR	-51.17	140.00	4.76	~10.5
5	898	2/3/2002	17:33	Tangaroa	CPR	-51.09	140.00	4.80	~10.5
5	899	2/3/2002	17:58	Tangaroa	CPR	-51.01	140.00	4.60	~10.5
5	900	2/3/2002	18:25	Tangaroa	CPR	-50.93	140.00	4.86	~10.5
5	901	2/3/2002	18:51	Tangaroa	CPR	-50.85	140.01	4.68	~10.5
5	902	2/3/2002	19:17	Tangaroa	CPR	-50.78	140.00	4.63	~10.5
5	903	2/3/2002	19:44	Tangaroa	CPR	-50.70	140.00	4.81	~10.5
5	904	2/3/2002	20:10	Tangaroa	CPR	-50.62	140.00	4.71	~10.5
5	905	2/3/2002	20:36	Tangaroa	CPR	-50.54	140.00	4.70	~10.5
5	906	2/3/2002	21:03	Tangaroa	CPR	-50.46	140.00	4.80	~10.5
5	907	2/3/2002	21:30	Tangaroa	CPR	-50.38	140.00	4.70	~10.5
5	908	2/3/2002	21:57	Tangaroa	CPR	-50.30	140.00	4.65	~10.5
5	909	2/3/2002	22:25	Tangaroa	CPR	-50.22	140.00	4.83	~10.5
5	910	2/3/2002	22:52	Tangaroa	CPR	-50.15	139.99	4.67	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**911**	2/3/2002	23:19	Tangaroa	CPR	-50.07	139.99	4.71	~10.5
5	**912**	2/3/2002	23:46	Tangaroa	CPR	-49.99	139.98	4.72	~10.5
5	**913**	3/3/2002	00:12	Tangaroa	CPR	-49.91	139.98	4.63	~10.5
5	**914**	3/3/2002	00:38	Tangaroa	CPR	-49.83	139.99	4.71	~10.5
5	**915**	3/3/2002	01:04	Tangaroa	CPR	-49.75	139.99	4.75	~10.5
5	**916**	3/3/2002	01:30	Tangaroa	CPR	-49.67	139.99	4.78	~10.5
5	**917**	3/3/2002	01:56	Tangaroa	CPR	-49.59	139.99	4.77	~10.5
5	**918**	3/3/2002	02:22	Tangaroa	CPR	-49.51	139.99	4.78	~10.5
5	**919**	3/3/2002	02:47	Tangaroa	CPR	-49.44	139.99	4.59	~10.5
5	**920**	3/3/2002	03:13	Tangaroa	CPR	-49.36	139.99	4.84	~10.5
5	**921**	3/3/2002	03:38	Tangaroa	CPR	-49.28	140.00	4.61	~10.5
5	**922**	3/3/2002	04:04	Tangaroa	CPR	-49.20	140.00	4.73	~10.5
5	**923**	3/3/2002	04:30	Tangaroa	CPR	-49.12	140.00	4.76	~10.5
5	**924**	3/3/2002	04:56	Tangaroa	CPR	-49.04	140.01	4.73	~10.5
5	**925**	3/3/2002	05:22	Tangaroa	CPR	-48.96	140.00	4.76	~10.5
5	**926**	3/3/2002	05:47	Tangaroa	CPR	-48.89	140.00	4.60	~10.5
5	**927**	3/3/2002	06:13	Tangaroa	CPR	-48.81	140.00	4.88	~10.5
5	**928**	3/3/2002	06:38	Tangaroa	CPR	-48.73	140.00	4.68	~10.5
5	**929**	3/3/2002	07:03	Tangaroa	CPR	-48.65	140.00	4.67	~10.5
5	**930**	3/3/2002	07:28	Tangaroa	CPR	-48.57	140.00	4.71	~10.5
5	**931**	3/3/2002	07:54	Tangaroa	CPR	-48.49	139.99	4.83	~10.5
5	**932**	3/3/2002	08:19	Tangaroa	CPR	-48.41	139.99	4.62	~10.5
5	**933**	3/3/2002	08:45	Tangaroa	CPR	-48.34	139.99	4.75	~10.5
5	**934**	3/3/2002	09:11	Tangaroa	CPR	-48.26	139.99	4.75	~10.5
5	**935**	3/3/2002	09:37	Tangaroa	CPR	-48.18	139.99	4.75	~10.5
5	**936**	3/3/2002	10:03	Tangaroa	CPR	-48.10	139.99	4.75	~10.5
5	**937**	3/3/2002	10:28	Tangaroa	CPR	-48.02	139.99	4.57	~10.5
5	**938**	3/3/2002	10:54	Tangaroa	CPR	-47.94	139.99	4.75	~10.5
5	**939**	3/3/2002	11:20	Tangaroa	CPR	-47.86	140.00	4.76	~10.5
5	**940**	3/3/2002	11:46	Tangaroa	CPR	-47.78	140.00	4.72	~10.5
5	**941**	3/3/2002	12:13	Tangaroa	CPR	-47.70	140.00	4.84	~10.5
5	**942**	3/3/2002	12:38	Tangaroa	CPR	-47.63	140.01	4.55	~10.5
5	**943**	3/3/2002	13:04	Tangaroa	CPR	-47.55	140.01	4.79	~10.5
5	**944**	3/3/2002	13:29	Tangaroa	CPR	-47.47	140.01	4.65	~10.5
5	**945**	3/3/2002	13:54	Tangaroa	CPR	-47.39	140.01	4.72	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
5	**946**	3/3/2002	14:20	Tangaroa	CPR	-47.31	140.00	4.84	~10.5
5	**947**	3/3/2002	14:45	Tangaroa	CPR	-47.23	140.00	4.63	~10.5
5	**948**	3/3/2002	15:11	Tangaroa	CPR	-47.16	139.99	4.78	~10.5
5	**949**	3/3/2002	15:37	Tangaroa	CPR	-47.08	139.99	4.74	~10.5
5	**950**	3/3/2002	15:59	Tangaroa	CPR	-47.02	140.00	3.53	~10.5
6	**951**	10/3/2002	07:31	Shirase	CPR	-65.43	140.01	4.90	~10.5
6	**952**	10/3/2002	08:10	Shirase	CPR	-65.34	140.00	4.98	~10.5
6	**953**	10/3/2002	08:50	Shirase	CPR	-65.26	140.00	5.02	~10.5
6	**954**	10/3/2002	09:31	Shirase	CPR	-65.17	140.00	5.08	~10.5
6	**955**	10/3/2002	10:11	Shirase	CPR	-65.09	140.00	4.92	~10.5
6	**956**	10/3/2002	10:52	Shirase	CPR	-65.01	140.00	4.99	~10.5
6	**957**	10/3/2002	11:34	Shirase	CPR	-64.93	140.02	5.07	~10.5
6	**958**	10/3/2002	12:14	Shirase	CPR	-64.85	140.06	4.94	~10.5
6	**959**	10/3/2002	12:55	Shirase	CPR	-64.76	140.08	5.07	~10.5
6	**960**	10/3/2002	13:35	Shirase	CPR	-64.68	140.03	4.91	~10.5
6	**961**	10/3/2002	14:18	Shirase	CPR	-64.60	139.98	5.08	~10.5
6	**962**	10/3/2002	15:02	Shirase	CPR	-64.52	140.00	4.94	~10.5
6	**963**	10/3/2002	15:46	Shirase	CPR	-64.43	140.01	5.09	~10.5
6	**964**	10/3/2002	16:28	Shirase	CPR	-64.35	140.01	4.90	~10.5
6	**965**	10/3/2002	17:09	Shirase	CPR	-64.27	140.01	4.99	~10.5
6	**966**	10/3/2002	17:51	Shirase	CPR	-64.19	140.01	5.06	~10.5
6	**967**	10/3/2002	18:32	Shirase	CPR	-64.10	140.00	4.96	~10.5
6	**968**	10/3/2002	19:14	Shirase	CPR	-64.02	140.00	5.07	~10.5
6	**969**	10/3/2002	19:56	Shirase	CPR	-63.94	140.01	4.94	~10.5
6	**970**	10/3/2002	20:41	Shirase	CPR	-63.85	140.02	5.08	~10.5
6	**971**	10/3/2002	21:22	Shirase	CPR	-63.79	140.00	4.97	~10.5
6	**972**	10/3/2002	21:57	Shirase	CPR	-63.88	140.01	4.98	~10.5
6	**973**	10/3/2002	22:34	Shirase	CPR	-63.96	140.00	4.95	~10.5
6	**974**	10/3/2002	22:45	Shirase	CPR	-63.97	140.01	1.28	~10.5
6	**975**	11/3/2002	01:50	Shirase	CPR	-63.93	140.01	4.87	~10.5
6	**976**	11/3/2002	02:25	Shirase	CPR	-63.85	140.00	5.06	~10.5
6	**977**	11/3/2002	02:59	Shirase	CPR	-63.76	140.00	5.03	~10.5
6	**978**	11/3/2002	03:33	Shirase	CPR	-63.68	140.00	4.95	~10.5
6	**979**	11/3/2002	04:08	Shirase	CPR	-63.60	140.00	5.03	~10.5
6	**980**	11/3/2002	04:43	Shirase	CPR	-63.51	140.00	5.05	~10.5

Transect Number	Sample Number	Date (D/M/Y)	Time (GMT)	Research Vessel	Net	Latitude (°S)	Longitude (°E)	Length of CPR sample (nautical miles)	Depth (m)
6	981	11/3/2002	05:16	Shirase	CPR	-63.43	140.00	4.92	~10.5
6	982	11/3/2002	05:50	Shirase	CPR	-63.35	140.01	4.98	~10.5
6	983	11/3/2002	06:25	Shirase	CPR	-63.26	140.01	5.05	~10.5
6	984	11/3/2002	06:59	Shirase	CPR	-63.18	140.02	4.95	~10.5
6	985	11/3/2002	07:35	Shirase	CPR	-63.10	140.03	5.03	~10.5
6	986	11/3/2002	08:13	Shirase	CPR	-63.01	140.03	5.04	~10.5
6	987	11/3/2002	08:52	Shirase	CPR	-62.93	140.03	5.03	~10.5
6	988	11/3/2002	09:29	Shirase	CPR	-62.85	140.00	4.98	~10.5
6	989	11/3/2002	10:07	Shirase	CPR	-62.77	140.00	4.99	~10.5
6	990	11/3/2002	10:44	Shirase	CPR	-62.68	140.01	4.94	~10.5
6	991	11/3/2002	11:22	Shirase	CPR	-62.60	140.00	5.11	~10.5
6	992	11/3/2002	11:57	Shirase	CPR	-62.52	140.00	4.92	~10.5
6	993	11/3/2002	12:33	Shirase	CPR	-62.43	140.00	5.03	~10.5
6	994	11/3/2002	13:08	Shirase	CPR	-62.35	140.00	4.94	~10.5
6	995	11/3/2002	13:44	Shirase	CPR	-62.26	140.00	5.09	~10.5
6	996	11/3/2002	14:19	Shirase	CPR	-62.18	140.00	4.94	~10.5
6	997	11/3/2002	14:55	Shirase	CPR	-62.10	139.99	4.97	~10.5
6	998	11/3/2002	15:32	Shirase	CPR	-62.02	139.99	5.09	~10.5
6	999	11/3/2002	16:05	Shirase	CPR	-61.93	139.99	5.00	~10.5
6	1000	11/3/2002	16:39	Shirase	CPR	-61.85	140.00	4.91	~10.5
6	1001	11/3/2002	17:14	Shirase	CPR	-61.77	140.00	5.01	~10.5
6	1002	11/3/2002	17:50	Shirase	CPR	-61.68	140.01	5.07	~10.5
6	1003	11/3/2002	18:25	Shirase	CPR	-61.60	140.01	4.97	~10.5
6	1004	11/3/2002	19:00	Shirase	CPR	-61.52	140.00	4.95	~10.5
6	1005	11/3/2002	19:35	Shirase	CPR	-61.43	140.01	5.01	~10.5
6	1006	11/3/2002	20:10	Shirase	CPR	-61.35	140.01	5.04	~10.5
6	1007	11/3/2002	20:45	Shirase	CPR	-61.27	140.02	5.02	~10.5
6	1008	11/3/2002	21:20	Shirase	CPR	-61.18	140.02	4.94	~10.5
6	1009	11/3/2002	21:58	Shirase	CPR	-61.10	140.00	4.99	~10.5
6	1010	11/3/2002	22:37	Shirase	CPR	-61.02	139.96	5.03	~10.5
6	1011	11/3/2002	22:45	Shirase	CPR	-61.01	139.97	0.75	~10.5

Appendix 2. The complete taxonomic list for samples presented in Appendix 1.

FORAMINFERA
RADIOLARIA
CILIOPHORA
Strombidium sp.
HYDROMEDUSAE
Arctapodema sp.
Hydromedusa
Pegantha sp.
Pegantha triloba
Solmundella bitentaculata
SIPHONOPHORAE
Chelophyes sp.
Diphyes antarctica
Lensia sp.
Siphonophore
Siphonophore nectophore
CTENOPHORA
MOLLUSCA
Cephalopoda
Squid sp.
Pteropoda
Clio pyramidata antarctica
Clione limacina antarctica
Diacria sp.
Limacina helicina antarctica
Limacina helicina antarctica forma *rangi*
Limacina inflata
Spongiobranchaea australis
POLYCHAETA
Alciopid
Iospilidae sp.
Maupasia coeca
Maupasia sp.
Pelagobia longicirrata
Phalacrophorus pictus
Polychaete sp. (parasite)
Tomopteris carpenteri
Tomopteris dunckeri
Tomopteris elegans
Tomopteris septentrionalis

Polychaeta continued...
Tompoteris planktonis
Tompoteris spp.
Travisiopsis lanceolata
Typhloscolex mulleri
Unidentified polychaete
Vanadis longissima
Vanadis sp.
OSTRACODA
COPEPODA
Aetedeopsis minor
Aetideus armatus
Calanoid copepods (small)
Calanoid Nauplius (large)
Calanoid Nauplius (small)
Calanoid sp (small)
Calanoides acutus
Calanus propinquus
Calanus simillimus
Calanus sp.
Calocalanus minutus
Calocalanus sp.
Candacia falcifera
Candacia maxima
Candacia sp.
Centropages bradyi
Clausocalanus brevipes
Clausocalanus laticeps
Clausocalanus sp.
Copepod Nauplius (large calanoid)
Copepod Nauplius (small calanoid)
Copepod Nauplius (small *Oithona*?)
Ctenocalanus citer
Ctenocalanus vanus
Eucalanus hyalinus
Eucalanus longiceps
Eucalanus sp.
Euchaeta marina
Euchaeta spp.
Euchirella rostrata
Euchirella rostromagna
Euchirella sp.
Haloptilus longicirrus
Haloptilus oxycephalus

Copepoda continued...	***Amphipoda continued...***
Harpacticoid	*Hyperia* sp.
Heterorhabdus austrinus	*Hyperiella dilatata*
Heterorhabdus sp.	*Hyperiella* sp.
Heterorhabdus spinifrons	Hyperiid spp.
Large copepod unidentified	*Hyperoche medusarum*
Lubbockia sp.	*Hyperoche* sp.
Lucicutia curta	*Phronima sedentaria*
Lucicutia macrocerca	Platysceloidea sp.
Mecynocera clausi	*Primno macropa*
Metridia gerlachei	*Themisto gaudichaudii*
Metridia lucens	*Vibilia antarctica*
Metridia sp.	*Vibilia armata*
Microcalanus pygmaeus	*Vibilia* sp.
Microsetella rosea	
Neocalanus tonsus	**EUPHAUSIACEA**
Oithona frigida	*Euphausia crystallorophias*
Oithona similis	*Euphausia frigida*
Oithona sp.	*Euphausia longirostris*
Oncaea antarctica	*Euphausia lucens*
Oncaea conifera	*Euphausia* nauplius
Oncaea curvata	*Euphausia similis*
Oncaea sp.	*Euphausia superba*
Paracalanus sp.	*Euphausia triacantha*
Paraeuchaeta antarctica	*Euphausia vallentini*
Paraeuchaeta barbarta	*Thysanoessa gregaria*
Paraeuchaeta biloba	*Thysanoessa macrura*
Paraeuchaeta exigua	*Thysanoessa macrura / vicina*
Paraeuchaeta sp.	
Pleuromamma borealis	**DECAPODA**
Pleuromamma piseki	Decapod megalopa
Pleuromamma robusta	Decapod sp.
Pleuromamma sp	Majidae zoea
Rhincalanus gigas	*Nematocarcinus* sp. (zoea)
Sapphirina sp.	Pandalidae sp. (zoea)
Scaphocalanus vervoorti	Sergestidae
Scolecithricella minor	
Scolecithricella sp	**CHAETOGNATHA**
Stephos longipes	Chaetognatha
Small calanoid copepodite (C1-3)	*Eukrohnia hamata*
Large calanoid copepodite (C1)	*Eukrohnia* sp.
Large calanoid copepodite (C2)	*Sagitta gazellae*
Large calanoid copepodite (C3)	*Sagitta marri*
Unidentified copepod	*Sagitta maxima*
	Sagitta sp.
AMPHIPODA	**APPENDICULARIA**
Cyllopus magellanicus	Appendicularia
Dairella latissima	*Oikopleura* spp.
	Fritillaria spp.

DOLIOLIDA	**Fish**
Doliolid	Fish egg
Doliolina muelleri (gonozooid)	Fish larvae
Doliolina muelleri (nurse)	Myctophid
	Gymnoscopelus sp.
SALPIDA	*Krefftichthyes andersoni*
Salpa thompsoni	*Notothenia augustifrons*
Salpa thompsoni (aggregate)	*Pleurogramma antarcticum*
Salpa thompsoni bud	*Protomyctophum* sp.
Salpa thompsoni solitary	

Appendix 3

Figure 1. Chapter 4 dendograms resulting from cluster analysis of **a.** night and **b.** day samples. Prior to analysis taxon abundance levels (individuals.m^{-3}) were $\log_{10}(x+1)$ transformed. Cluster analysis was performed using the Bray-Curtis dissimilarity metric and Un-Weighted Pair Group Average linkage.

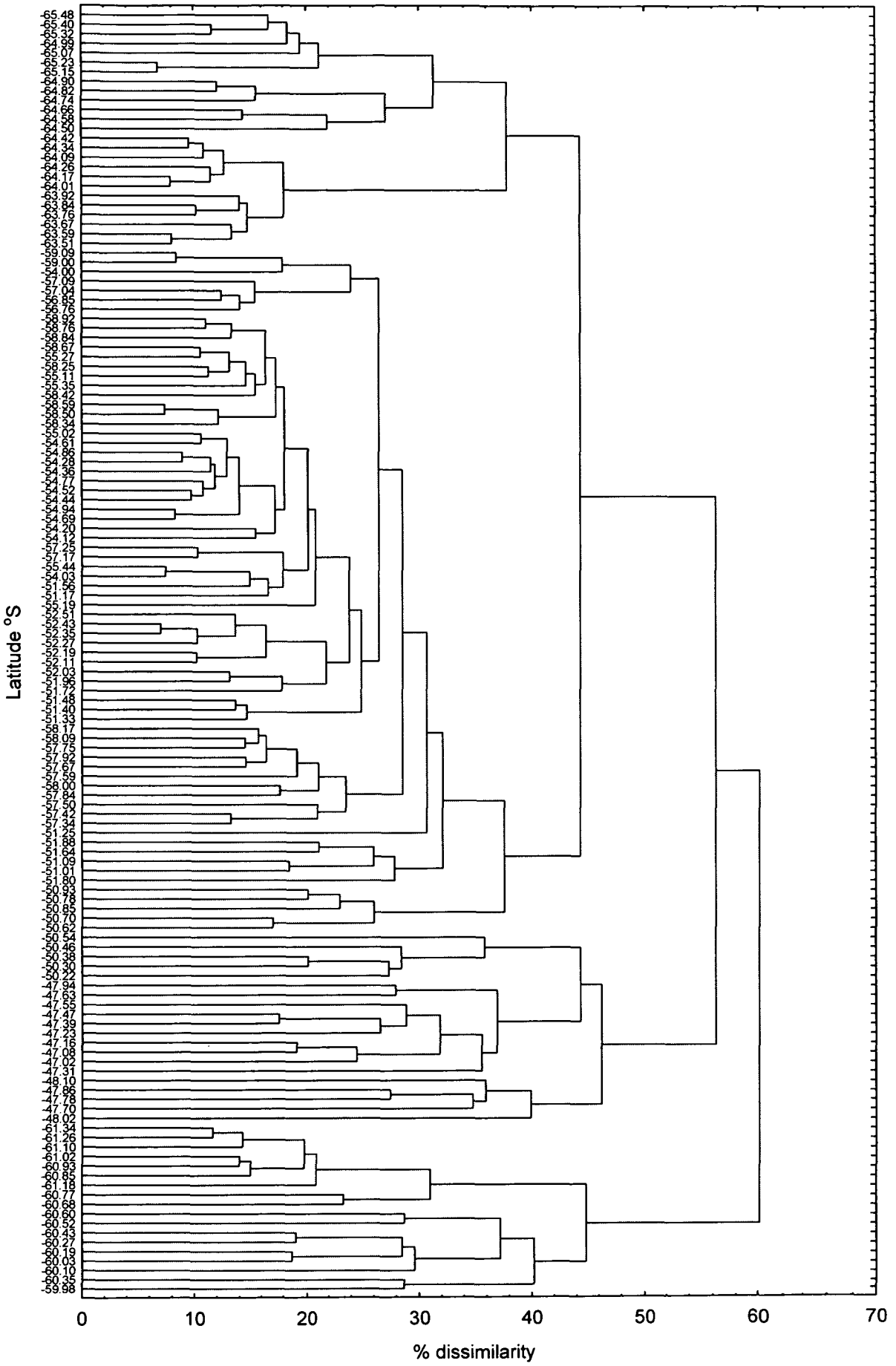

Figure 1.a. Night cluster

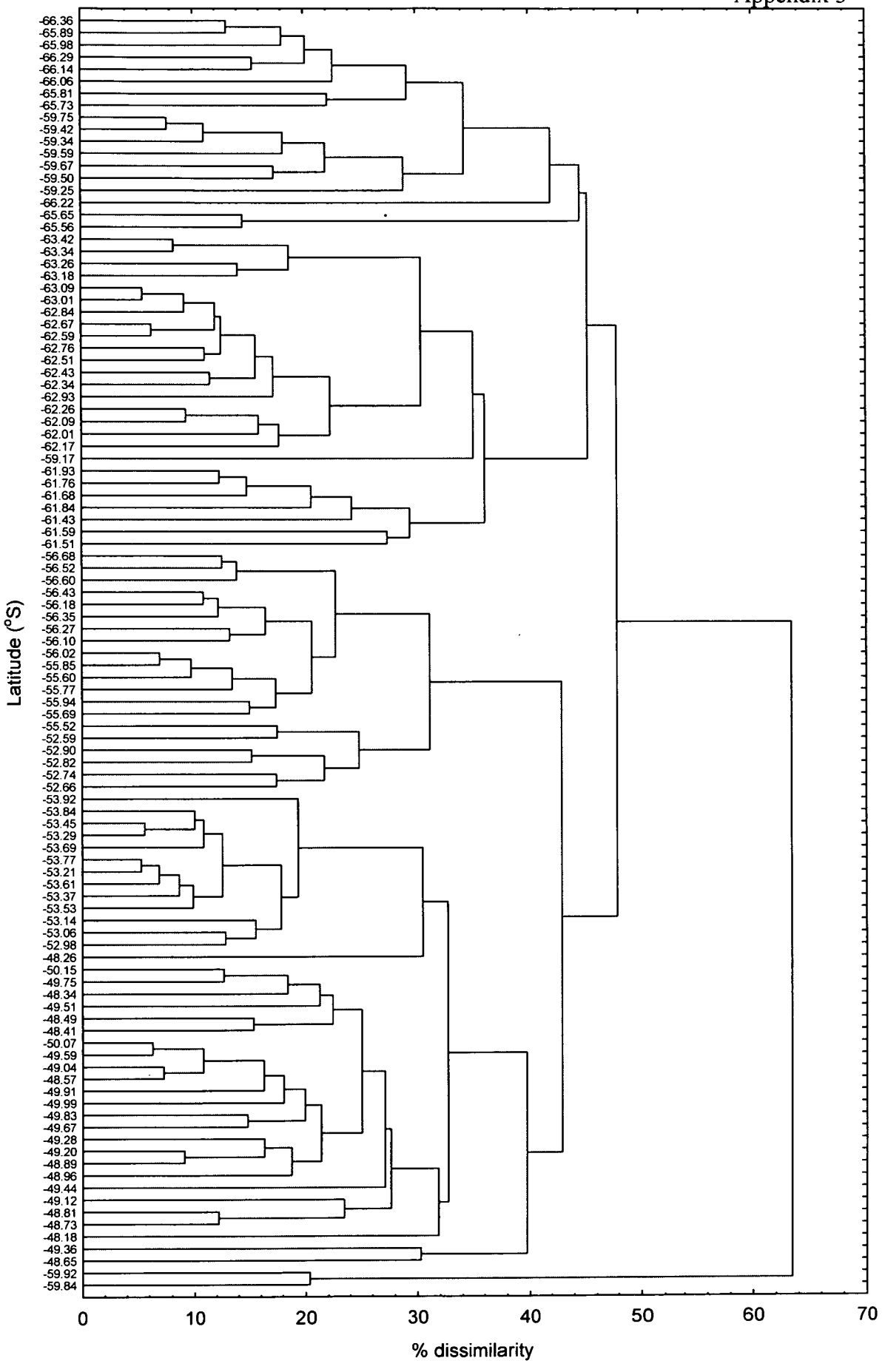

Figure 1.b. Day cluster

Figure 2. Clusters from the analysis of the seasonal succession of zooplankton communities in the Seasonal Ice Zone. Cluster analysis was performed by Un-Weighted Pair Group Average linkage of using **i.** Presence / Absence data and Sorenson's Coefficient **ii.** $\log_{10}(x+1)$ abundance data and the Bray-Curtis dissimilarity measure **iii.** raw abundance data for taxa occurring in $\geq 20\%$ of samples and the Manhattan Metric. Separate analyses were performed for **night and day** data.

a. night Presence / Absence
b. night Bray-Curtis
c. night Manhattan Metric
d. day Presence / Absence
e. day Bray-Curtis
f. day Manhattan Metric

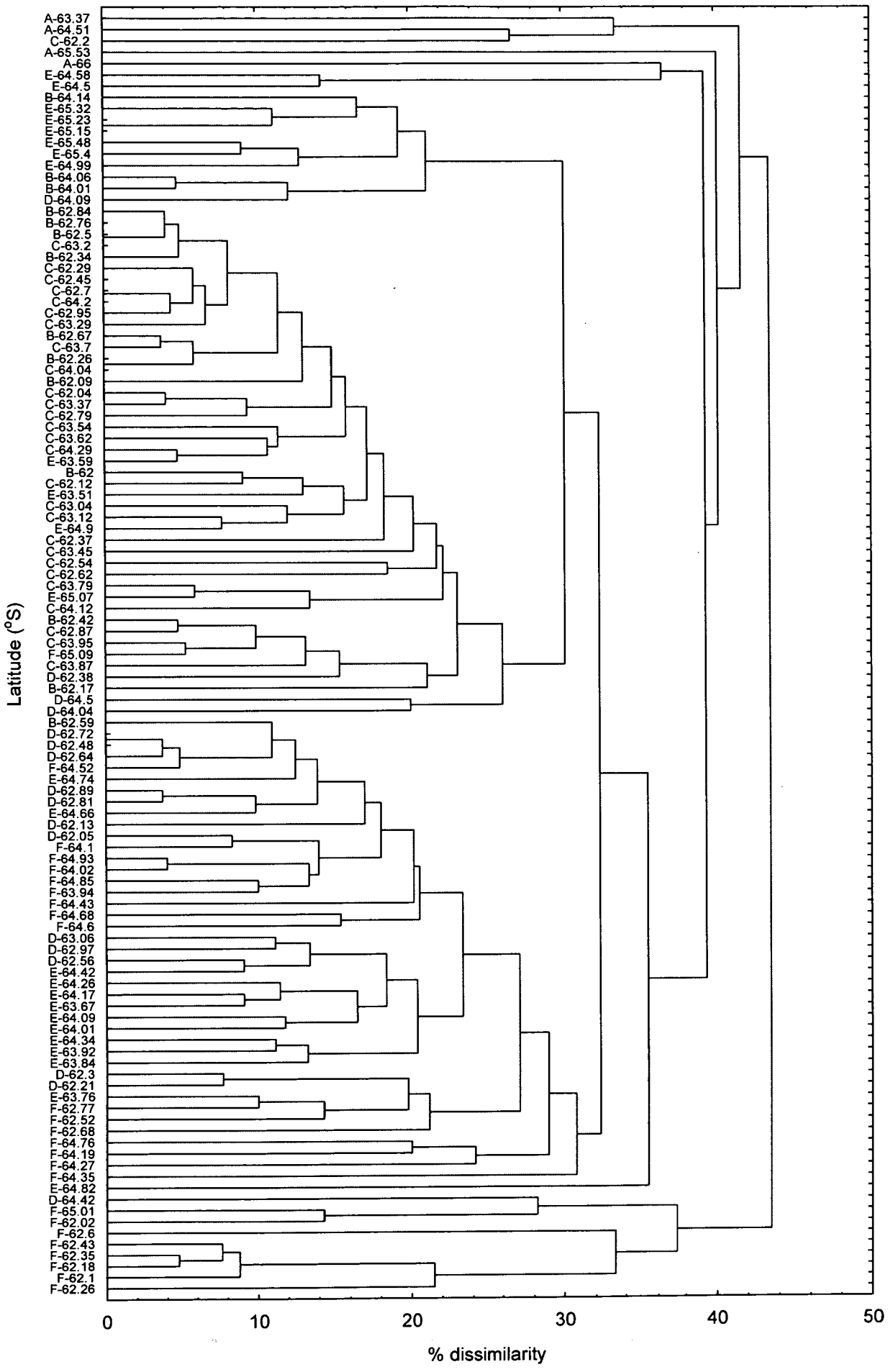

Figure 2.a. Night Presence / Absence

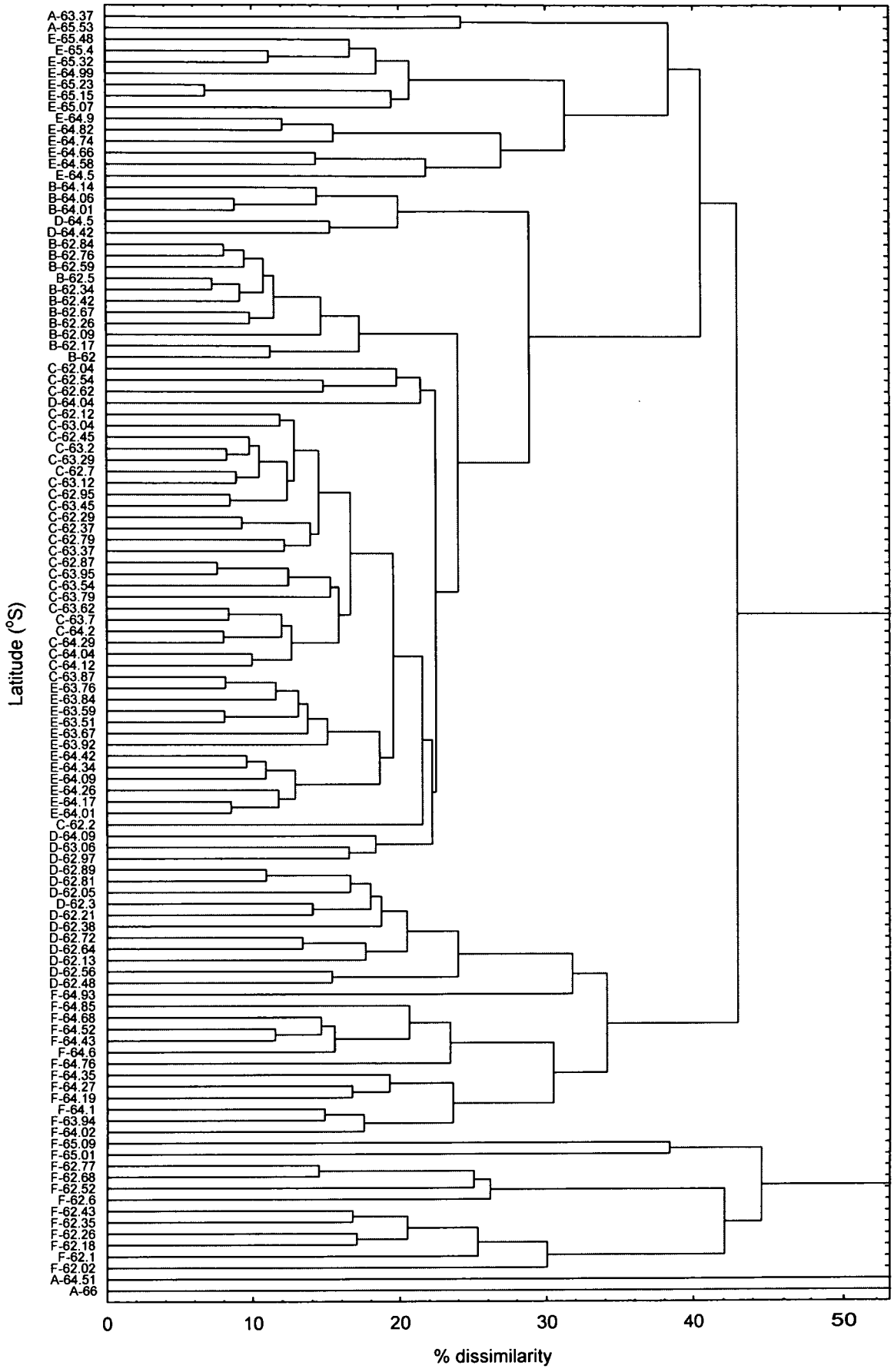

Figure 2.b. Night Bray-Curtis

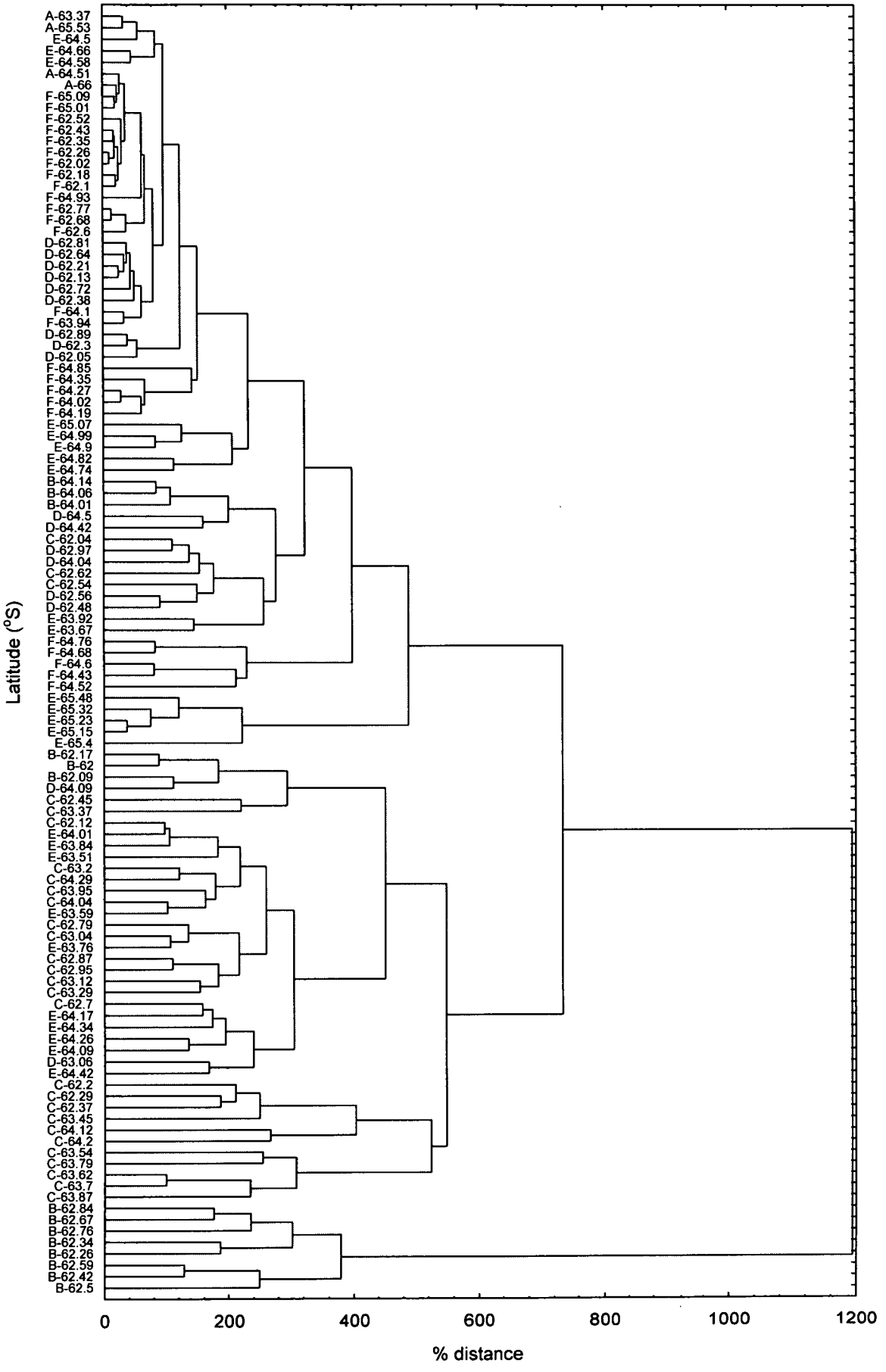

Figure 2.c. Night Manhattan / Metric

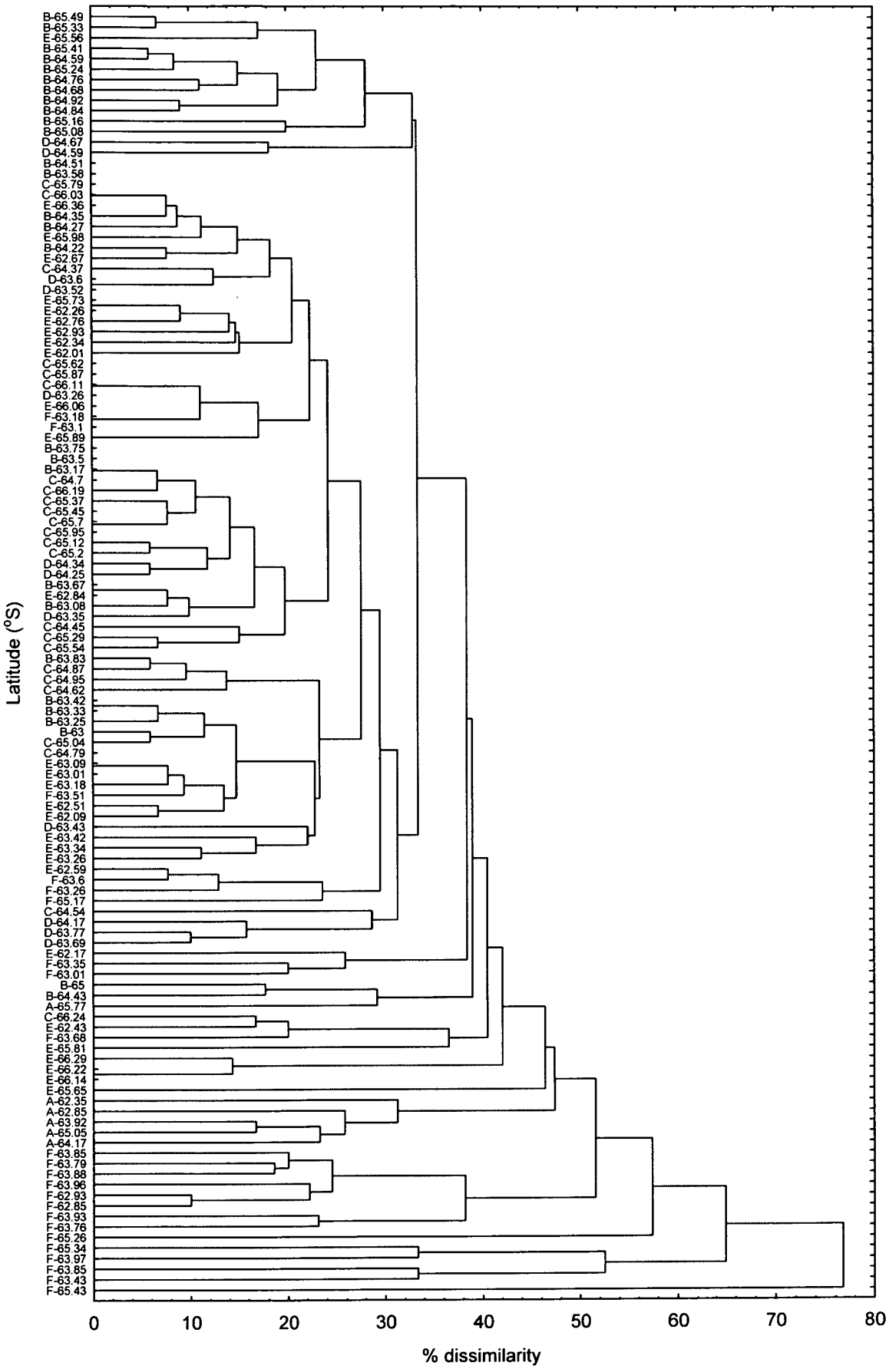

Figure 2.d. Day Presence / Absence

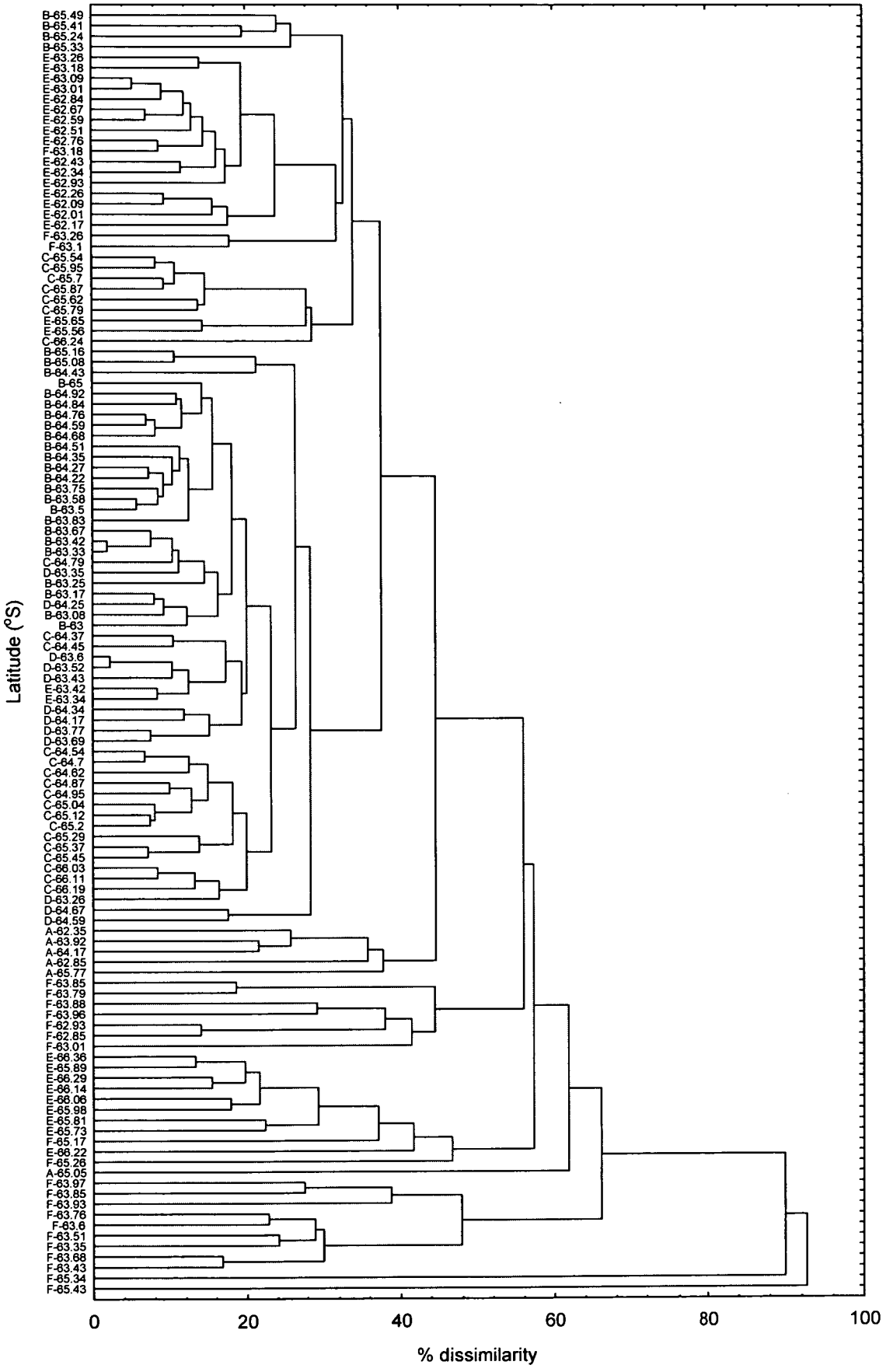

Figure 2.e. Day Bray-Curtis

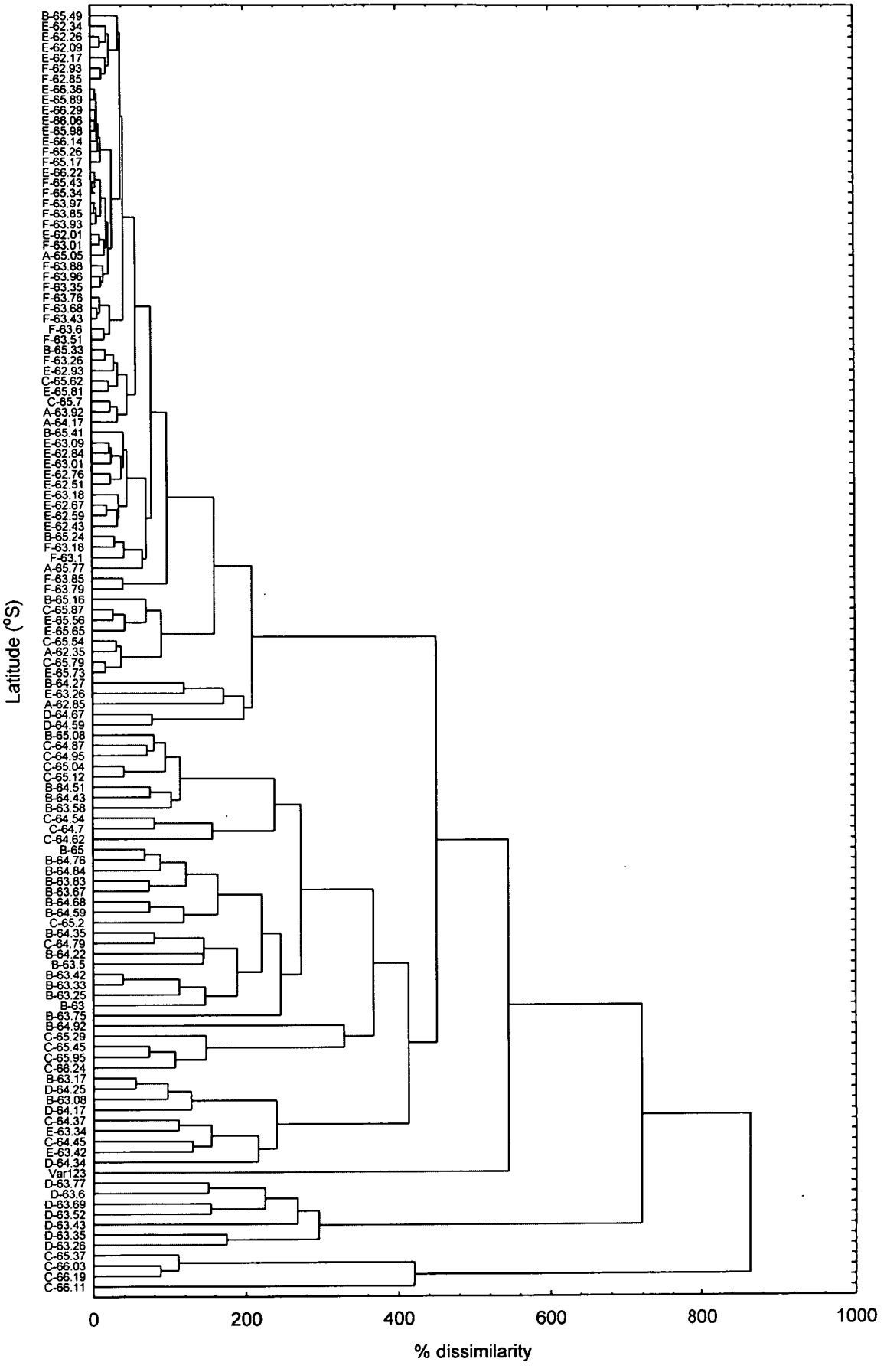

Figure 2.f. Day Manhattan Metric

Figure 3. Clusters from analysis of the seasonal succession of zooplankton communities in the Sub-Antarctic Zone to Polar Frontal Zone. Cluster analysis was performed by Un-Weighted Pair Group Average linkage of using **i.** Presence / Absence data and Sorenson's Coefficient **ii.** $\log_{10}(x+1)$ abundance data and the Bray-Curtis dissimilarity measure **iii.** raw abundance data for taxa occurring in ≥ 20% of samples and the Manhattan Metric. Separate analyses were performed for **night and day** data.

a. night Presence / Absence
b. night Bray-Curtis
c. night Manhattan Metric
d. day Presence / Absence
e. day Bray-Curtis
f. day Manhattan Metric

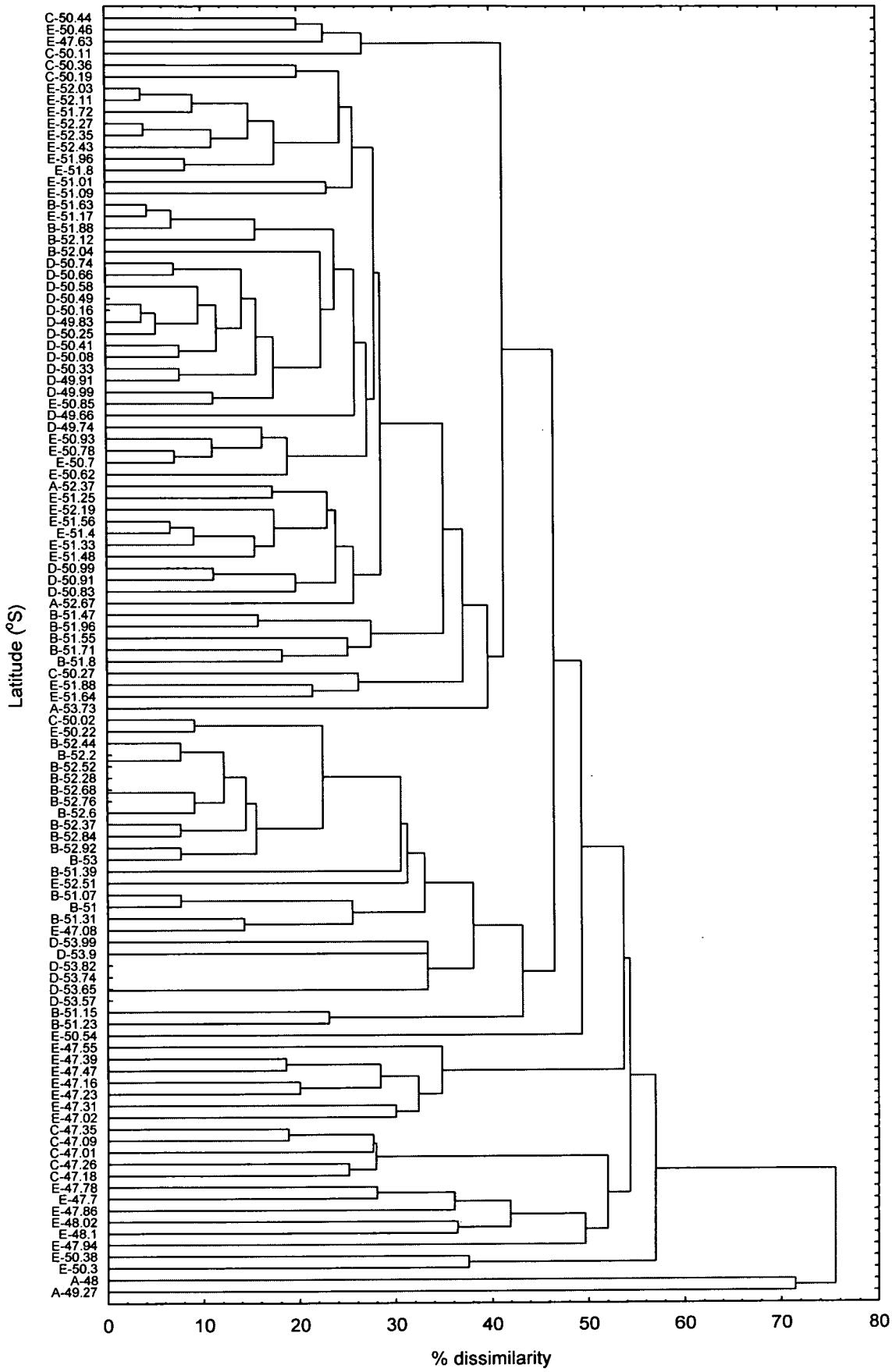

Figure 3.a. Night Presence / Absence

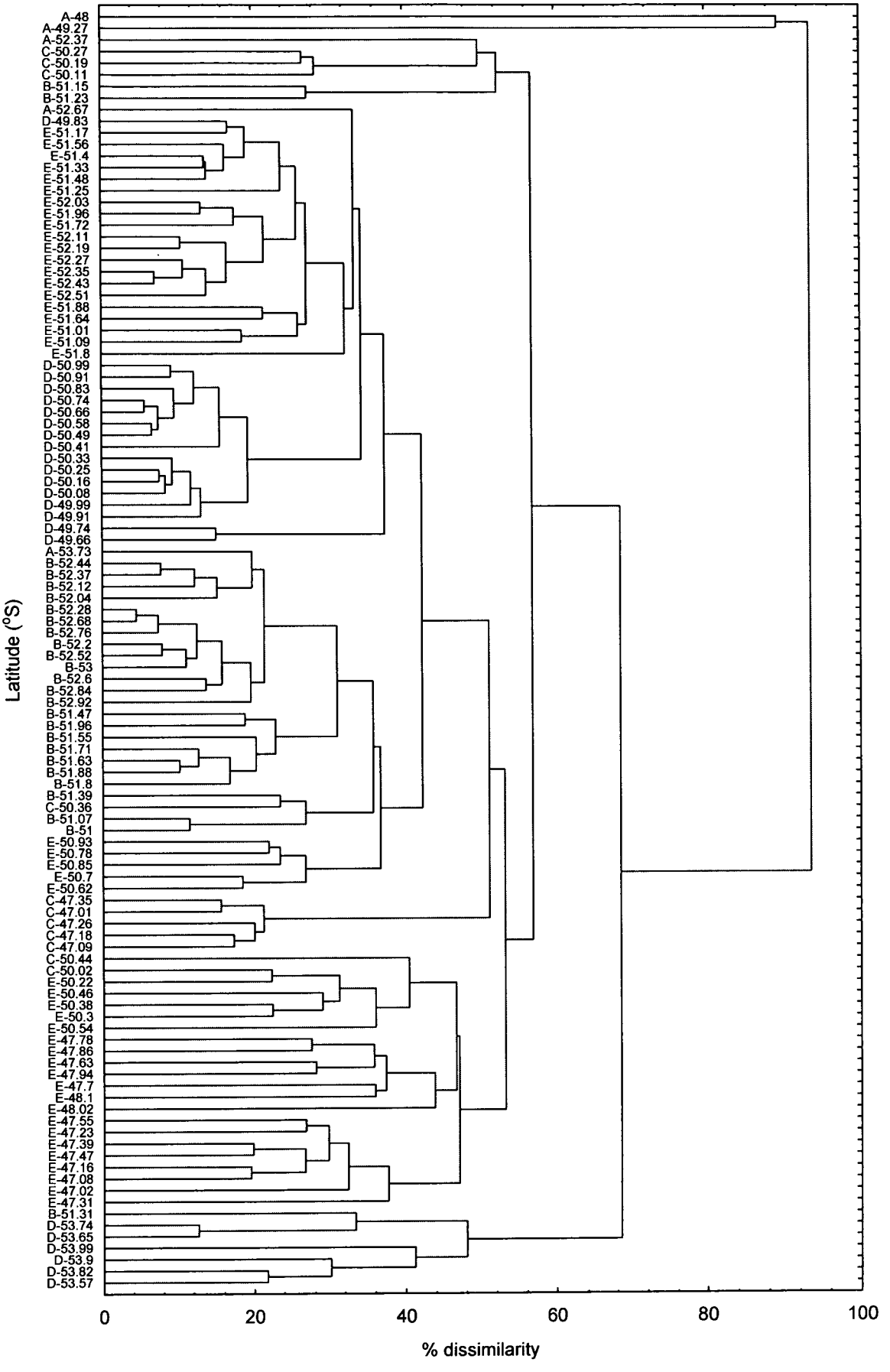

Figure 3.b. Night Bray-Curtis

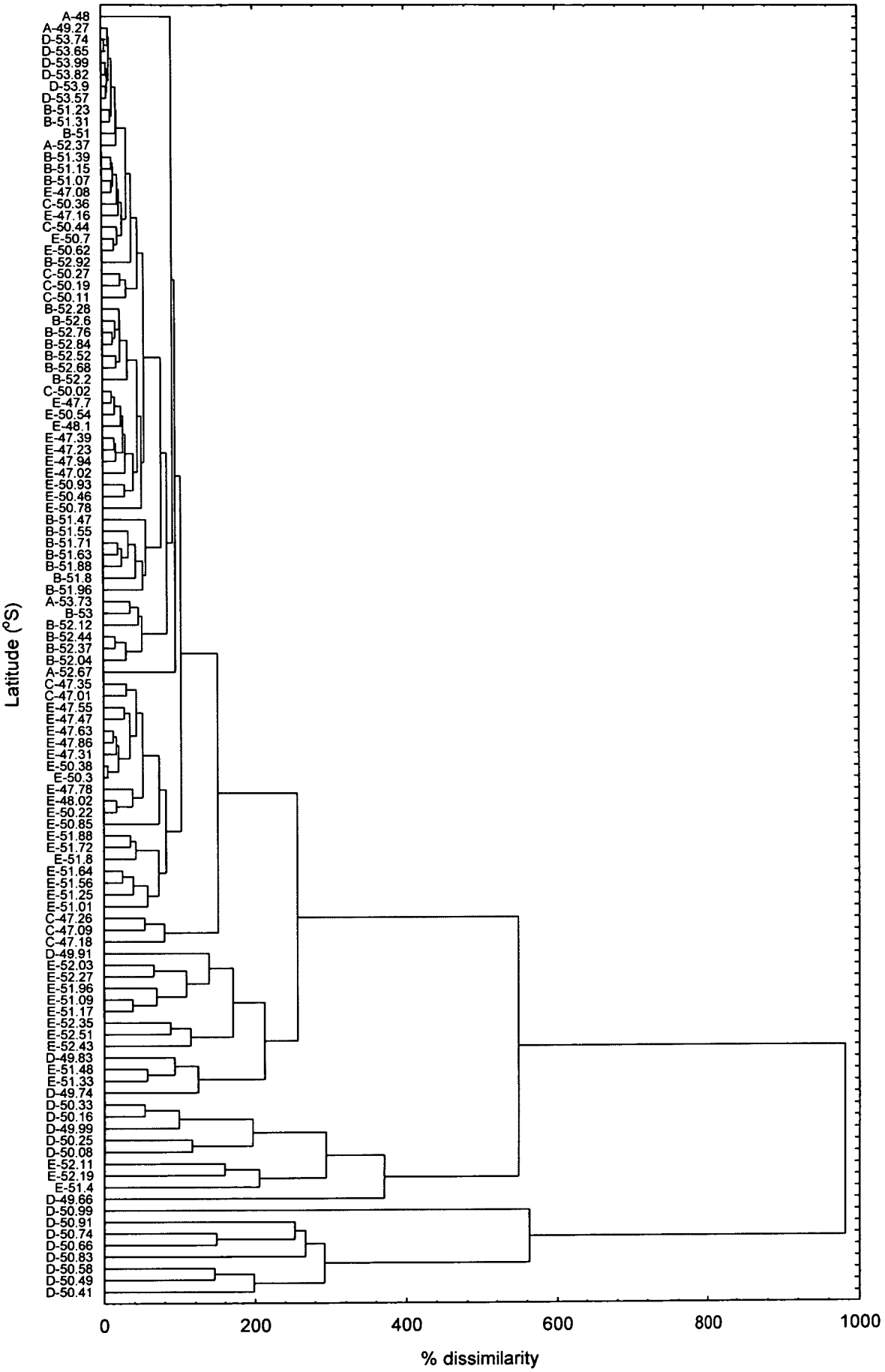

Figure 3.c. Night Manhattan Metric

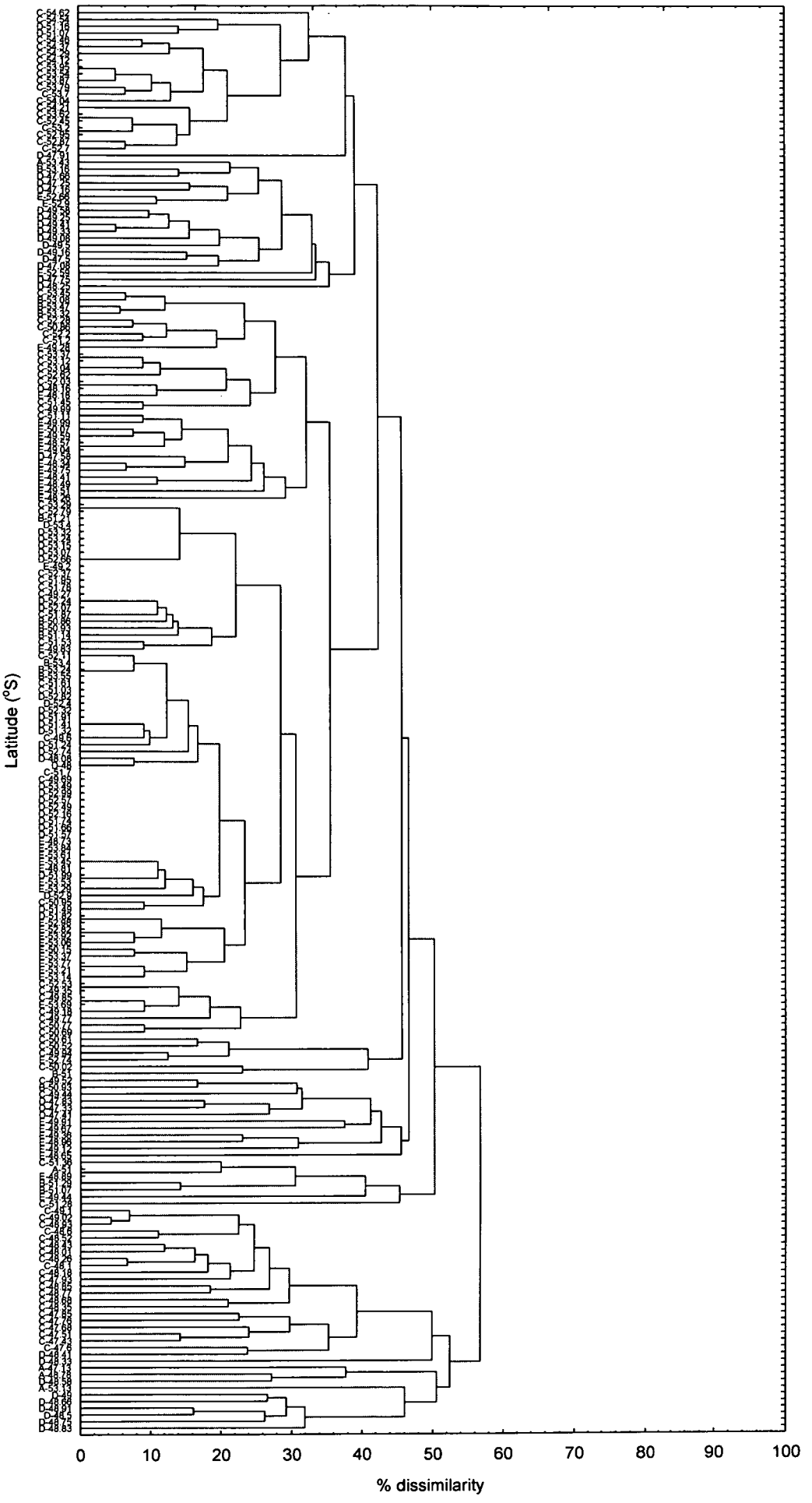

Figure 3.d. Day Presence / Absence

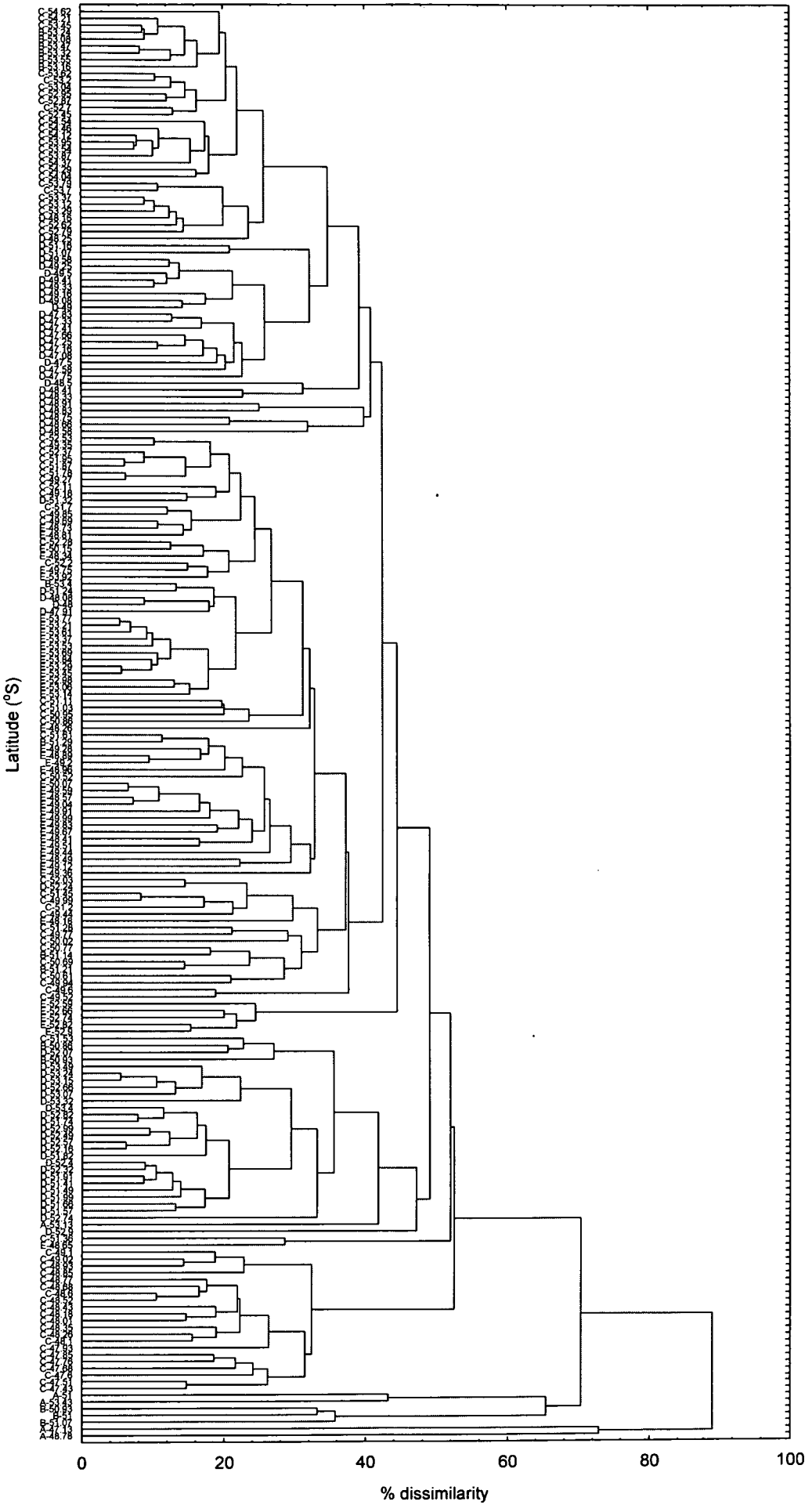

Figure 3.e. Day Bray-Curtis

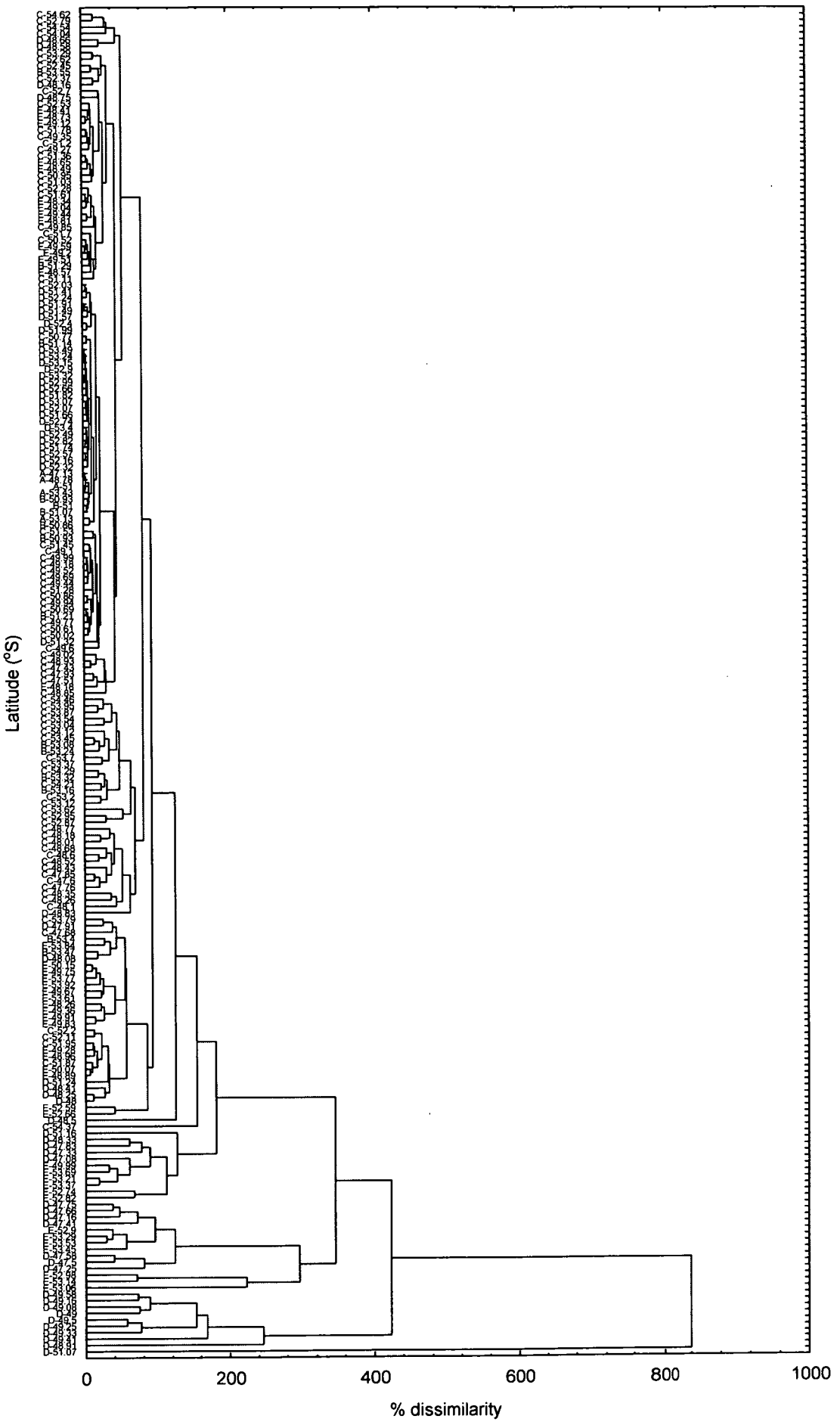

Figure 3.f. Day Manhattan Metric

Appendix 4. Zooplankton and densities (individuals.m^{-3}) recorded at NORPAC net stations between 62°S and 66°S, from 22-28 November.

Table 1. 0-20 m depth zone

Latitude (°S)	**-62.35**	**-62.85**	**-63.37**	**-63.92**	**-64.17**	**-64.51**	**-65.05**	**-65.53**	**-65.77**	**-66.00**
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Foraminifera	3.723	9.024	14.057	4.816	14.439	8.742	1.904	14.152	2.461	0.071
Hydromedusa	0.677	0.000	0.260	0.000	0.000	1.692	0.000	0.000	0.000	0.000
Solmundella bitentaculata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Siphonophore / nectophore	0.000	0.000	0.000	0.000	0.000	0.282	0.000	1.231	0.000	0.000
Dimophyes arctica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Phalacrophorous pictus	0.677	10.779	0.456	1.171	0.902	0.564	0.141	3.692	20.305	0.000
Travisiopsis lanceolata	0.000	0.000	0.065	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Typhloscolex mullerii	0.000	0.000	0.000	0.000	0.056	0.000	0.000	0.615	0.000	0.000
Tomopterus carpenteri	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris planktonis	0.338	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris sp.	0.000	0.000	0.716	0.000	0.000	0.423	0.000	1.231	0.000	0.000
Vanadis sp.	0.000	0.000	0.000	0.000	0.000	0.071	0.000	0.000	0.000	0.000
Clio pyrimidata antarctica	0.000	0.000	0.000	0.000	0.226	0.000	0.000	0.000	0.000	0.000
Limacina spp.	0.000	0.251	0.000	0.390	0.000	0.212	0.141	0.000	0.000	0.000
Spongiobranchea australis	0.677	0.000	0.000	0.390	0.113	0.141	0.071	0.000	0.000	0.000
Ostracoda	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Unidentified copepodite	44.332	22.310	8.070	21.086	15.792	1.974	0.635	4.307	1.846	0.000
Aetidius armatus	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Calanoides acutus	1.015	0.752	0.651	1.432	0.846	0.000	0.282	1.846	8.614	0.423
Calanus simillimus	0.000	0.000	0.195	0.000	0.000	1.410	0.071	0.000	0.000	0.071
Calanus propinquus	0.000	0.063	0.065	0.000	0.000	0.000	0.000	0.000	0.000	0.212
Clausocalanus brevipes	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Clausocalanus laticeps	0.338	1.504	0.000	0.000	0.000	0.282	0.000	0.000	0.000	0.000
Ctenocalanus citer	6.768	32.588	3.905	3.124	2.256	0.564	1.622	3.692	1.231	6.627
Euchirella sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Haloptilus oxycephalus	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Harpacticoid	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Heterostylites longicornis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Metridia gerlachei	0.000	0.000	0.000	0.000	0.000	0.282	0.000	0.000	0.000	2.045
Metridia lucens	0.000	0.000	0.260	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Metridia copepodites (C1-4)	0.000	0.000	0.000	0.000	0.000	0.282	0.000	0.000	0.000	0.071

Table 1 *continued.* 0-20 m depth zone

Latitude (°S)	-62.35	-62.85	-63.37	-63.92	-64.17	-64.51	-65.05	-65.53	-65.77	-66.00
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Oithona frigida	0.000	0.000	0.260	0.000	0.226	0.000	0.000	0.000	0.000	0.000
Oithona similis	15.228	67.682	22.908	4.816	16.244	2.820	9.095	14.152	32.610	4.583
Oncaea sp.	0.000	0.251	0.000	0.000	0.677	0.000	0.000	0.615	0.000	0.071
Paraeuchaeta antarctica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Paraeuchaeta spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Rhincalanus gigas	3.046	2.507	1.367	0.390	2.200	1.058	0.000	0.000	0.000	0.000
Scolecithricella minor	0.000	0.000	0.260	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stephos longipes	3.723	2.005	0.781	0.521	1.128	0.000	0.705	0.000	0.000	0.846
Primno macropa	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Scina sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Themisto gaudichaudii	0.000	0.251	0.065	0.130	0.000	0.000	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina	0.000	0.063	0.000	0.000	0.000	2.115	0.000	0.077	0.000	0.000
Thysanoessa macrura / vicina C1	0.000	0.251	0.000	0.000	0.000	0.000	0.141	0.000	0.000	0.000
Thysanoessa macrura / vicina C2	0.000	3.008	0.325	0.000	0.169	0.071	0.635	3.692	2.461	0.000
Thysanoessa macrura / vicina C3	0.000	6.016	0.195	0.130	0.282	0.635	0.282	0.615	0.000	0.000
Thysanoessa macrura / vicina F1	0.000	0.000	0.195	0.130	0.169	0.282	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina F2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C1	0.000	2.256	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C2	0.000	2.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C3	0.000	2.256	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida F1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia crystalorophias	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Oplophoridae	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.071
Chaetognath spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Eukrohnia hamata	1.354	0.752	0.325	0.390	0.000	0.071	0.000	0.000	0.000	0.000
Sagitta gazellae	0.000	0.000	0.000	0.000	0.113	0.000	0.000	0.000	0.000	0.000
Sagitta marri	0.000	0.000	0.000	0.000	0.000	0.141	0.000	0.000	0.000	0.000
Appendicularia	110.660	60.914	40.804	48.809	49.408	4.653	0.423	54.146	23.381	0.423
Salpa thompsoni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gymnoscopelus sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 2. 20-50 m depth zone

Latitude (°S)	**-62.35**	**-62.85**	**-63.37**	**-63.92**	**-64.17**	**-64.51**	**-65.05**	**-65.53**	**-65.77**	**-66.00**
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Foraminifera	2.884	18.019	19.470	25.029	33.292	35.239	1.298	24.392	8.575	0.189
Hydromedusa	0.000	0.000	0.506	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Solmundella bitentaculata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Siphonophore / nectophore	0.192	0.000	0.000	0.313	0.000	0.420	0.000	0.000	0.000	0.000
Dimophyes arctica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Phalacrophorous pictus	0.769	0.146	0.506	0.313	0.412	0.210	0.144	3.296	6.533	0.000
Travisiopsis lanceolata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Typhloscolex mullerii	0.000	0.000	0.506	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tomopterus carpenteri	0.000	0.000	0.000	0.039	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris planktonis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris sp.	0.577	0.439	2.023	0.469	0.082	0.210	0.000	0.659	0.000	0.000
Vanadis sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Clio pyrimidata antarctica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Limacina spp.	0.000	0.146	0.253	0.196	0.330	0.210	0.096	0.000	0.817	0.047
Spongiobranchea australis	0.192	0.146	0.506	0.039	0.082	0.000	0.192	0.000	0.408	0.000
Ostracoda	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Unidentified copepodite	31.149	19.777	13.654	22.526	15.492	4.195	1.106	7.252	2.450	0.047
Aetidius armatus	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Calanoides acutus	1.538	1.611	0.759	1.251	0.659	0.210	1.058	3.296	13.883	0.521
Calanus simillimus	0.000	0.146	0.000	0.000	0.000	0.210	0.385	0.000	0.000	0.000
Calanus propinquus	0.000	0.000	0.506	0.000	0.330	0.000	0.000	1.318	1.225	0.000
Clausocalanus brevipes	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Clausocalanus laticeps	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ctenocalanus citer	15.959	8.790	8.850	6.883	8.900	6.712	2.355	17.799	0.408	8.377
Euchirella sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Haloptilus oxycephalus	0.192	0.146	0.000	0.626	0.000	0.210	0.000	0.000	0.000	0.000
Harpacticoid	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Heterostylites longicornis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Metridia gerlachei	0.000	0.000	0.506	0.000	0.000	0.000	0.000	3.296	0.000	1.467
Metridia lucens	0.000	0.000	1.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Metridia copepodites (C1-4)	0.000	0.146	0.000	0.313	0.000	0.000	0.048	1.318	0.000	0.047

Table 2 *continued.* 20-50 m depth zone

Latitude (°S)	-62.35	-62.85	-63.37	-63.92	-64.17	-64.51	-65.05	-65.53	-65.77	-66.00
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Oithona frigida	0.192	0.000	0.253	0.000	0.000	0.000	0.048	0.000	0.000	0.000
Oithona similis	6.345	19.191	54.870	9.073	23.403	15.942	4.807	32.962	61.251	6.295
Oncaea sp.	0.385	0.000	0.000	0.000	0.330	0.000	0.000	1.318	1.225	0.000
Paraeuchaeta antarctica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Paraeuchaeta spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.318	0.000	0.426
Rhincalanus gigas	2.115	2.930	5.563	3.441	5.274	8.810	0.000	0.000	0.408	0.142
Scolecithricella minor	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Stephos longipes	1.731	0.732	0.759	0.000	0.330	0.000	0.096	0.000	0.817	0.142
Primno macropa	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Scina sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Themisto gaudichaudii	0.192	0.146	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina C1	0.000	0.000	0.000	0.000	0.000	0.000	0.096	1.978	0.817	0.000
Thysanoessa macrura / vicina C2	0.577	0.586	1.264	0.469	0.453	1.049	0.865	5.933	3.267	0.000
Thysanoessa macrura / vicina C3	0.961	1.465	0.759	0.156	0.700	1.468	0.481	0.000	0.817	0.000
Thysanoessa macrura / vicina F1	0.000	0.879	0.759	0.939	0.247	1.888	0.096	0.659	0.000	0.000
Thysanoessa macrura / vicina F2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C1	0.000	0.000	0.000	0.000	0.000	0.210	0.000	0.000	0.000	0.000
Euphausia frigida C2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C3	0.000	0.000	0.253	0.000	0.041	0.000	0.000	0.000	0.000	0.000
Euphausia frigida F1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia crystalorophias	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.142
Oplophoridae	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Chaetognath spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Eukrohnia hamata	0.385	0.586	0.253	0.156	0.082	0.210	0.000	0.659	0.000	0.000
Sagitta gazellae	0.000	0.000	0.000	0.000	0.082	0.000	0.048	0.000	0.000	0.000
Sagitta marri	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Appendicularia	68.451	36.331	49.055	42.549	50.926	33.561	1.058	60.650	42.059	0.331
Salpa thompsoni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gymnoscopelus sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3. 50-100 m depth zone

Latitude (°S)	-62.35	-62.85	-63.37	-63.92	-64.17	-64.51	-65.05	-65.53	-65.77	-66.00
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Foraminifera	8.428	26.636	15.449	34.943	15.567	19.459	6.050	10.842	3.662	0.084
Hydromedusa	0.192	0.000	0.000	3.305	0.000	0.000	0.103	0.000	0.000	0.000
Solmundella bitentaculata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Siphonophore / nectophore	0.192	0.218	0.055	1.417	0.451	0.212	0.000	0.197	0.000	0.000
Dimophyes arctica	0.000	0.000	0.000	0.000	0.226	0.212	0.000	0.000	0.000	0.000
Phalacrophorous pictus	0.383	0.655	0.221	0.826	1.128	0.000	0.718	0.591	0.523	0.000
Travisiopsis lanceolata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Typhloscolex mullerii	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tomopterus carpenteri	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris planktonis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris sp.	0.192	0.437	0.552	0.354	0.000	0.212	0.000	0.000	0.262	0.000
Vanadis sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Clio pyrimidata antarctica	7.854	0.218	0.110	0.472	0.000	1.692	0.000	0.000	0.000	0.000
Limacina spp.	0.192	0.000	0.000	0.000	0.226	0.212	0.000	0.000	0.131	0.000
Spongiobranchea australis	0.192	0.218	0.221	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ostracoda	1.149	0.000	0.883	0.000	0.226	0.000	0.000	0.591	0.392	0.000
Unidentified copepodite	12.642	10.261	11.918	16.999	14.664	3.173	1.333	4.337	1.831	0.028
Aetidius armatus	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Calanoides acutus	0.766	0.655	0.883	1.180	1.354	0.212	1.538	1.183	3.400	0.167
Calanus simillimus	0.575	1.092	0.883	0.590	0.677	0.846	0.103	0.197	0.000	0.000
Calanus propinquus	0.000	0.000	0.110	0.000	0.000	0.000	0.000	0.197	0.131	0.167
Clausocalanus brevipes	0.192	0.000	0.000	0.000	0.226	0.000	0.000	0.197	0.000	0.028
Clausocalanus laticeps	0.000	0.000	0.000	0.118	0.000	0.000	0.103	0.000	0.000	0.000
Ctenocalanus citer	28.541	14.628	22.512	17.471	22.335	14.594	7.281	7.491	8.370	6.350
Euchirella sp.	0.000	0.000	0.000	0.472	0.000	0.000	0.000	0.000	0.000	0.000
Haloptilus oxycephalus	1.724	0.218	0.110	0.944	0.451	0.635	0.000	0.000	0.000	0.000
Harpacticoid	0.192	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Heterostylites longicornis	0.000	0.000	0.000	0.000	0.226	0.000	0.000	0.000	0.000	0.000
Metridia gerlachei	0.000	0.218	0.883	0.000	0.000	0.000	0.103	0.986	0.785	0.390
Metridia lucens	0.000	0.000	0.883	0.000	0.226	0.000	0.000	0.000	0.131	0.000
Metridia copepodites (C1-4)	0.766	0.218	2.207	3.305	2.030	0.000	0.000	2.760	0.916	0.084

Table 3 *continued.* 50-100 m depth zone

Latitude (°S)	-62.35	-62.85	-63.37	-63.92	-64.17	-64.51	-65.05	-65.53	-65.77	-66.00
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Oithona frigida	0.192	0.437	21.187	2.833	0.451	0.635	0.000	0.197	0.392	0.056
Oithona similis	8.811	16.811	0.000	12.277	24.140	9.729	7.794	11.434	13.471	8.133
Oncaea sp.	9.961	4.585	3.973	1.417	1.805	0.635	0.000	0.000	0.131	0.000
Paraeuchaeta antarctica	0.000	0.000	0.000	0.000	0.000	0.000	0.103	0.000	0.000	0.000
Paraeuchaeta spp.	0.766	0.000	1.766	1.417	1.805	0.000	0.103	0.789	0.000	0.529
Rhincalanus gigas	4.406	3.930	3.200	10.743	5.866	5.076	0.820	0.197	0.065	0.000
Scolecithricella minor	0.766	0.218	1.766	2.361	0.451	0.212	0.000	0.394	0.000	0.000
Stephos longipes	0.000	0.655	0.000	0.944	0.451	0.000	0.308	0.197	0.131	0.084
Primno macropa	0.383	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Scina sp.	0.000	0.000	0.028	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Themisto gaudichaudii	0.000	0.000	0.441	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina	0.000	0.000	0.248	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina C1	1.149	0.873	1.435	0.472	0.677	2.538	0.923	2.563	0.262	0.028
Thysanoessa macrura / vicina C2	2.107	1.747	0.883	1.889	1.805	3.807	1.333	1.380	1.308	0.028
Thysanoessa macrura / vicina C3	2.107	0.873	1.104	1.180	2.707	3.384	0.820	0.197	0.000	0.000
Thysanoessa macrura / vicina F1	0.000	0.873	0.772	0.708	0.226	0.635	0.000	0.197	0.000	0.000
Thysanoessa macrura / vicina F2	0.000	0.000	0.000	0.118	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida	0.000	0.000	0.441	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C1	0.192	0.000	0.110	0.000	0.226	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C2	0.383	0.000	0.221	0.000	0.000	0.212	0.000	0.000	0.000	0.000
Euphausia frigida C3	0.000	0.000	0.000	0.472	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida F1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.197	0.000	0.000
Euphausia crystalorophias	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.056
Oplophoridae	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Chaetognath spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Eukrohnia hamata	8.045	0.437	1.324	4.014	2.933	2.961	0.513	0.789	0.131	0.028
Sagitta gazellae	0.192	0.218	0.110	0.000	0.226	0.423	0.000	0.000	0.131	0.000
Sagitta marri	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Appendicularia	55.359	32.531	19.532	58.671	32.487	13.113	4.204	17.150	9.809	0.362
Salpa thompsoni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gymnoscopelus sp.	0.000	0.000	0.028	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 4. 100-150 m depth zone

Latitude (°S)	-62.35	-62.85	-63.37	-63.92	-64.17	-64.51	-65.05	-65.53	-65.77	-66.00
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Foraminifera	29.903	70.738	33.991	26.001	44.038	25.688	10.374	8.663	5.061	0.220
Hydromedusa	0.475	0.393	0.301	0.327	0.180	0.567	0.000	0.180	0.000	0.000
Solmundella bitentaculata	0.000	0.000	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Siphonophore / nectophore	0.158	0.000	0.000	0.000	0.000	0.378	0.000	0.000	0.000	0.000
Dimophyes arctica	0.000	0.000	0.000	0.000	0.180	0.189	0.095	0.000	0.353	0.000
Phalacrophorous pictus	0.633	0.000	0.902	0.491	0.361	0.000	0.381	0.902	0.589	0.274
Travisiopsis lanceolata	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Typhloscolex mullerii	0.000	0.000	0.000	0.164	0.000	0.000	0.000	0.000	0.000	0.055
Tomopterus carpenteri	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris planktonis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tompoteris sp.	0.316	0.000	0.226	0.164	0.000	0.000	0.190	0.361	0.235	0.000
Vanadis sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Clio pyrimidata antarctica	6.803	1.572	0.075	0.164	0.180	2.644	0.095	0.023	0.000	0.000
Limacina spp.	0.158	0.786	0.075	0.164	0.000	0.000	0.190	0.180	0.118	0.000
Spongiobranchea australis	0.316	0.000	0.000	0.164	0.000	0.378	0.095	0.180	0.000	0.000
Ostracoda	0.791	0.393	0.301	0.000	0.180	0.189	0.666	2.527	3.060	0.000
Unidentified copepodite	18.986	13.362	7.520	16.680	8.122	3.022	0.857	2.527	1.295	0.055
Aetidius armatus	0.158	0.000	0.000	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Calanoides acutus	1.108	2.358	0.602	1.145	0.902	0.189	0.571	0.902	0.824	0.384
Calanus simillimus	0.949	1.179	0.301	0.164	0.180	0.000	0.286	0.000	0.000	0.000
Calanus propinquus	0.316	0.000	0.075	0.000	0.000	0.000	0.000	0.180	0.589	0.165
Clausocalanus brevipes	0.000	0.000	0.000	0.000	0.180	0.000	0.286	0.000	0.118	0.000
Clausocalanus laticeps	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ctenocalanus citer	23.100	18.471	13.236	8.176	13.356	17.188	11.041	5.595	6.474	5.762
Euchirella sp.	0.000	0.000	0.000	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Haloptilus oxycephalus	0.316	0.393	1.203	0.164	0.000	0.944	0.000	0.180	0.353	0.000
Harpacticoid	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Heterostylites longicornis	0.000	0.000	0.000	0.000	0.180	0.000	0.000	0.000	0.000	0.000
Metridia gerlachei	0.158	0.000	0.301	0.000	0.000	0.000	0.190	0.722	2.825	0.713
Metridia lucens	0.158	0.393	1.203	0.491	0.000	0.756	0.190	0.000	0.000	0.000
Metridia copepodites (C1-4)	0.633	3.144	3.911	2.289	1.624	2.833	0.476	2.707	3.531	0.384

Table 4 *continued.* 100-150 m depth zone

Latitude (°S)	-62.35	-62.85	-63.37	-63.92	-64.17	-64.51	-65.05	-65.53	-65.77	-66.00
Station	**S80**	**S82**	**S83**	**S87**	**S89**	**S90**	**S93**	**S95**	**S98**	**S100**
Oithona frigida	1.740	4.323	4.813	4.415	5.956	5.100	0.381	0.180	1.766	1.537
Oithona similis	7.594	18.864	9.927	5.723	21.839	8.877	8.947	10.468	10.476	5.597
Oncaea sp.	12.816	12.969	9.024	7.195	3.249	5.289	0.190	1.805	1.530	0.055
Paraeuchaeta antarctica	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.000	0.000
Paraeuchaeta spp.	0.158	1.965	2.707	1.145	1.805	3.966	0.761	2.346	1.648	0.604
Rhincalanus gigas	4.747	10.218	2.030	2.943	5.415	2.267	0.381	0.361	0.353	0.000
Scolecithricella minor	0.316	1.572	3.911	0.981	1.985	1.700	0.286	0.180	0.118	0.000
Stephos longipes	0.158	0.393	0.000	0.491	0.180	0.000	0.095	0.000	0.118	0.329
Primno macropa	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.180	0.000	0.000
Scina sp.	0.000	0.000	0.000	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Themisto gaudichaudii	0.158	0.393	0.301	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Thysanoessa macrura / vicina	0.000	0.000	0.038	0.000	0.000	0.000	0.000	0.023	0.000	0.000
Thysanoessa macrura / vicina C1	1.424	3.930	0.752	1.962	1.624	2.644	1.142	1.805	2.354	0.000
Thysanoessa macrura / vicina C2	0.949	1.965	0.677	4.415	2.166	2.644	1.332	0.361	2.354	0.055
Thysanoessa macrura / vicina C3	0.791	3.144	0.602	3.434	0.722	3.778	0.857	0.000	0.118	0.000
Thysanoessa macrura / vicina F1	0.475	0.786	0.902	1.635	0.541	0.567	0.095	0.000	0.000	0.000
Thysanoessa macrura / vicina F2	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C1	0.158	0.393	0.075	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida C2	0.000	0.000	0.000	0.164	0.180	0.000	0.000	0.000	0.118	0.000
Euphausia frigida C3	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia frigida F1	0.000	0.000	0.000	0.164	0.000	0.000	0.000	0.000	0.000	0.000
Euphausia crystalorophias	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Oplophoridae	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Chaetognath spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.118	0.000
Eukrohnia hamata	7.436	4.716	2.557	2.453	3.610	6.044	1.904	1.083	1.059	0.220
Sagitta gazellae	0.000	0.000	0.602	0.000	0.361	0.567	0.000	0.000	0.118	0.055
Sagitta marri	0.000	0.000	0.301	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Appendicularia	42.719	33.404	17.522	36.794	22.741	14.544	3.331	9.024	14.831	0.220
Salpa thompsoni	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gymnoscopelus sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000